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Multiple Magnet Independent Levitation and Motion Control using a Single Coil Array

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***Abstract*— In this paper we investigate and demonstrate independent control and manipulation of multiple levitated magnets using a single planar array of cylindrical coils. Tracked motion results are given for two levitated magnets where each magnet follows a motion trajectory in close proximity to the other. Stable levitation of both magnets together requires accurate modeling and real-time calculation of force and torque interactions between all coils and magnets, as well as between the two levitated magnets. We aim to further develop the concept of multiple magnet levitation to enable the use of magnets as robotic fingers to grasp and manipulate small objects.**

An optical motion tracking system supplies the rigid-body position and orientation of the magnets as needed for feedback control, using three infrared emitters fixed to each magnet as markers. Each cylindrical magnet is controlled in three degrees of freedom in position and two degrees of freedom in rotation, leaving the rotation about the cylindrical axis uncontrolled. The forces and torques on the two magnets are generated by an array of 22 cylindrical coils, as a redundant control system. We plan to extend and improve these preliminary results to more complex motions and interactions through more sophisticated control and calibration methods.

I. INTRODUCTION

Magnetic levitation systems can provide many potential advantages to different application areas because the non-contact sensing and actuation in levitated motion control eliminates friction and other disturbances caused by contact with solid objects. Furthermore, the open-loop dynamics to be controlled are only those of a single rigid-body moving part with its corresponding mass and moments of inertia. These properties together offer the possibility of precise position and force control together, as well as programmable, configurable spatial rigid-body compliance of the levitated object. Although the rigid-body dynamics to be controlled are relatively simple, the challenges in the development of long-range magnetic levitation motion control systems are in the complexity of the electromagnetic modeling and the design of responsive, precise control systems.

We have demonstrated that our table-top scale magnetic levitation setup, modeling, and control methods allow independent control of multiple levitated bodies using a single array of cylindrical coils. The motion trajectories of each magnet can be specified independently in both translation and rotation at all times. To our knowledge and literature searches, this is an original result.

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A brief survey of similar published magnetic levitation system implementations is given in Section II. Section III describes the essential modeling, design, and control methods used in our two-magnet leviation system. Section IV describes details of our system implementation, including position sensing, current actuation, and the real-time controller. Section V presents the preliminary results from our system and Section VI concludes and describes further planned work in development.

II. BACKGROUND

A comprehensive review of magnetic methods in robotics is given by Abbot *et al* in [1]. This review includes not only magnetic leviataion systems, but robotic systems in which magnetic forces are used to produce motion.

Levitation systems are particularly advantageous for precision fabrication, assembly, and parts handling systems using levitated planar motors [2]. Typical levitated planar motor systems use straight, flat coil windings which extend in both directions across the entire length and width of a flat stator, and levitated platforms which contain four 1D multiple magnet arrays arranged in a square [3]. Levitation heights are limited to 2 to 3 mm.

Recently commercialized systems from Planar Motor Inc. and Beckhoff allow multiple stators to be tiled together and control multiple levitated platforms independently according to certain limitations. Significant magnetic interaction between different platforms is avoided due to the small levitation heights, and each coil wire current is whenever off whenever more than one levitated platform is located above it along its length to prevent any single current from generating forces on more than one platform at a time. With this method, the forces in the direction of motion of each platform are briefly left unactuated as they pass each another in either direction during a brief period as they completely 'overlap' one another as viewed from the side. The coasting momentum of the moving platforms and the frictionless motion during levitation enable these passing maneuvers to be executed smoothly, as described in the patent [4].

Large air gap magnetic levitation systems using cylindrical coils have been developed as suspension systems for wind tunnel testing [5] [6]. The advantages of magnetic levitation for wind tunnels are that the absence of a solid support structure for the tested model does not disturb the airflow around it, and that the forces and torques on the model from the airflow can be estimated very accurately since the aerodynamics forces and gravitational forces together correspond directly to the forces and torques generated by the levitation system.

Control of swarms of magnetic microbots is a research topic that has produced considerable development and recognition in recent years [7]. These swarms or clusters of magnetic capsules move together but are not controlled independently. Multiple microbots are controlled independently in [8], but these are not levitated. Control of magnetic capsules without the need for optical position sensing is of particular interest for medical applications, as the controlled motion of magnetic capsules inside the body could potentially be used for diagnosis, drug delivery, biopsy, and tumor excision in a non-invasive, non-surgical manner.

The general magnetic levitation and control methods developed in our laboratory are summarized in [9]. More details regarding design and implementation are provided in [10]. We have levitated platforms containing up to 6 cylindrical magnets, using arrays of up to 27 coils. Rigid-body translation ranges are up to 200 mm in the horizontal plane, easily extendable by adding more coils to the array, and up to 50 mm of levitation height, limited by overheating of the coils. Unlimited rotation ranges in all directions have been demonstrated with a levitated ball containing multiple magnets [11] . A selection of the levitated platforms is shown in Fig. 1.

Our coil arrays and control systems make levitation feasible for a large range of sizes and masses of the levitated platform. The limitations are that levitation of high mass platforms may require excessive currents which would overheat the coils and damage the wire insulation, and levitation of very small, lightweight platforms may require sensing and control bandwithds higher than our system can deliver, due to the fast rotational dynamics of small objects to be controlled.

A similar system using square coils is described in [12].

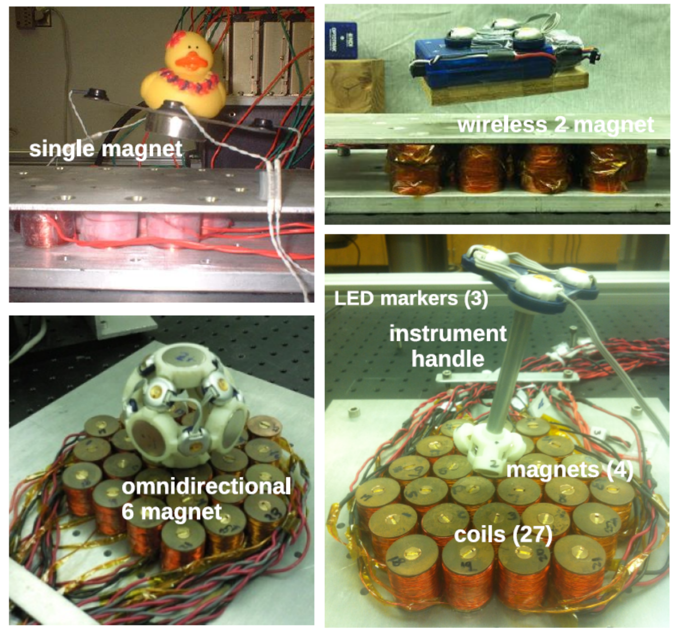

Fig. 1. Previous levitation systems from our laboratory with variable numbers of coils and magnets

III. METHODS

To lift and stabilize the motion of one or more levitated magnets with a coil array, detailed electromagnetic models of the forces and torques generated on the magnets from the coil currents are needed. At each update of the motion tracker we use precomputed electromagnetic force and torque modeling data to compile a transformation matrix between the set of coil currents and the vectors of all forces and torques generated on each magnet, corresponding to the updated rigid-body position and orientation of each magnet.

The force and torque vectors needed to support and stabilize the motion of the magnets are also calculated at each motion tracking update according to proportional-derivative controllers implemented for each motion degree of freedom. The pseudoinverse of the current to force and torque transformation matrix is then used to calculate the currents needed to produce the desired forces and torques for the controllers.

A. Magnet and Coil Forces and Torques

To calculate the transformation from coil currents to the forces and torques on a magnet with a given position and orientation, we use a numerical model of forces and torques generated on a single magnet from a single coil over the full predicted range of magnet positions and orientations. The model is precalculated and stored in a lookup table, and may be obtained from computational modeling or from force and torque experimental measurements. The point dipole magnetic model often used in electromagnetic modeling is not recommended for this application because the dimensions of the magnets and coils and the distances between them are of similar magnitudes and the dimensions of the magnets and coils have a significant effect on the magnetic fields and the resulting forces and torques.

The *Radia* electromagnetic modeling software [13] was used to model the forces and torques between a single magnet and coil and between two identical magnets. The results obtained from the *Radia* package have been found to be more consistently accurate than those from *ANSYS* and other packages, and its computational time is significantly faster. Calculated and measured electromagnetic forces and torques were directly compared in [10] for similar coils, magnets, and distances and these were found to agree to within 5% throughout the given motion ranges.

Forces between two cylindrical magnets on the same plane with variable relative orientations were also calculated using *Radia*. The horizontal force between two sample magnets with either parallel or opposite vertical magnetization axes is shown in Fig. 2 as a function of their horizontal separation distance. In this configuration, parallel magnetization of the two magnets produces repulsive forces between them, and opposite magnetization produces attractive forces. In Fig. 3, the forces and torques between the two magnets at a separation distance of 50 mm are shown as one magnet is rotated with respect to the other about the x axis defined by

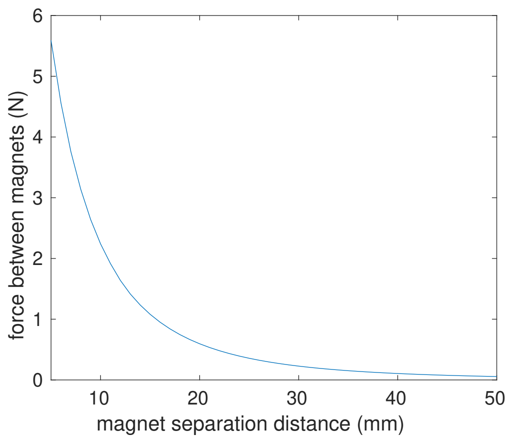

Fig. 2. Horizontal force between magnets with parallel or opposite orientation

the line between the two magnet centers, and the y axis which is perpendicular to both the x axis and the magnetization axis.

Due to the radial symmetry of the coils and magnets, the precomputed force and torque data may be stored as a 4D lookup tables indexed by the vertical and radial distance, tilt angle and tilt direction between a single magnet and coil. Each element of the lookup table contains a force or torque component produced on the magnet by a 1.0 A current in the coil. Force and torque data are calculated at each millimeter of vertical and radial separation, and at each 10 degrees of tilt and tilt direction. Linear interpolations of the lookup table data are used during levitation control. The coordinate transformation calculations from the cylindrical coordinate representation of the lookup table data to the cartesian coordinates used in the transformation matrix are described in detail in [9].

B. Combined Actuation

At each update of the levitation control code, the force and torque contributions from a 1.0 A current in each coil according to the relative position and orientation between each coil and magnet are combined into a transformation matrix which gives the total forces and torques produced on the magnets from all the coil currents together. For levitation of two magnets with 5 degrees of freedom of controlled motion for each, the force-torque vector F determined by the transformation matrix contains 10 elements. When using 22 coils for levitation, the transformation matrix A between the currents and forces and torques generated by them is 10x22 elements, and the current vector I has 22 elements. These together define the linear system of equations

$$F = AI, \quad (1)$$

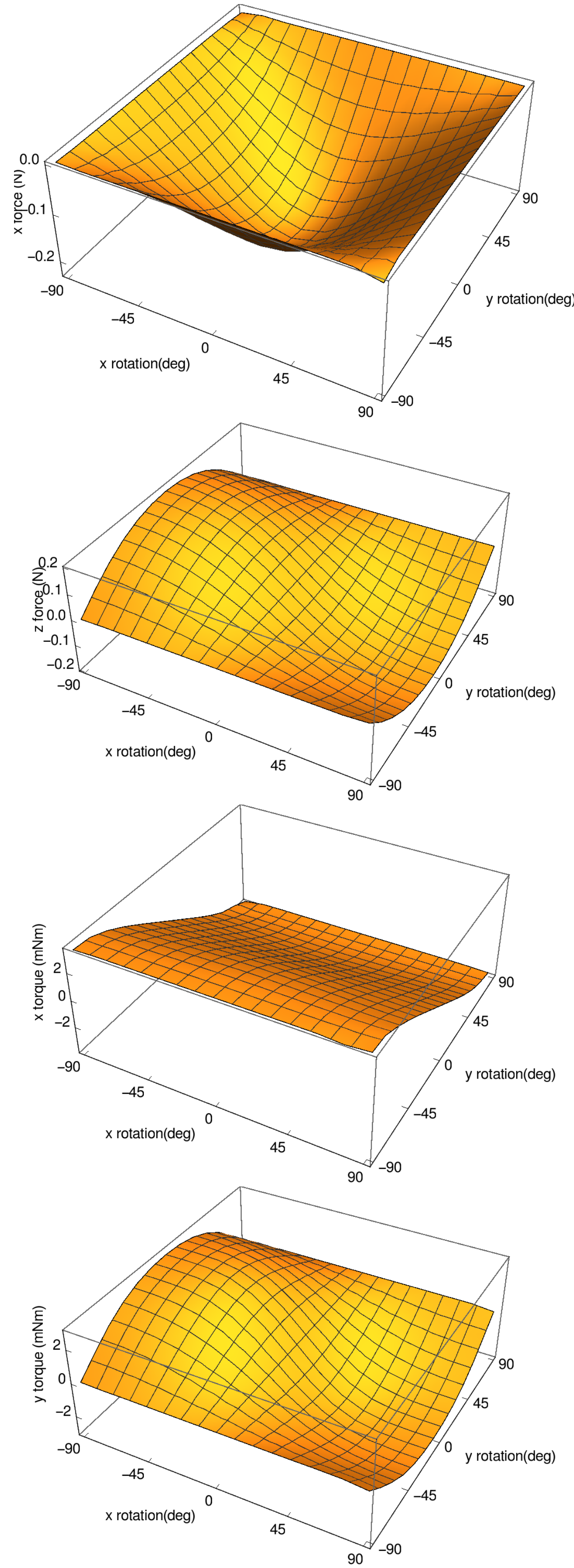

Fig. 3. Forces and torques between magnets at 50 mm separation as one magnet is rotated about its x and y axes

with elements of the force and torque vectors and the current vector given in

$$\begin{bmatrix} f_{1x} \\ f_{1y} \\ f_{1z} \\ \tau_{1x} \\ \tau_{1y} \\ f_{2x} \\ f_{2y} \\ f_{2z} \\ \tau_{2x} \\ \tau_{2y} \end{bmatrix} = \begin{bmatrix} a_{1,1} & \cdots & a_{1,22} \\ \vdots & \ddots & \vdots \\ a_{10,1} & \cdots & a_{10,22} \end{bmatrix} \begin{bmatrix} I_1 \\ \vdots \\ I_{22} \end{bmatrix}. \tag{2}$$

The forces and torques on the magnets from the coils are nonlinear with respect to position and orientation, but linear with respect to coil currents at a given rigid-body position and orientation. Since these equations are an under-determined linear system, the pseudoinverse of the A matrix can be used to calculate the coil currents to produce the desired set forces and torques on both magnets with the minimum power requirements, as the pseudoinverse produces the sum of least squares solution, and the electrical power produced by the coils is proportional to the sum of squared coil currents.

If the number of coils is less than the total number of degrees of freedom or the pseudoinverse of the A matrix cannot be calculated, then then total system of levitated magnets cannot be controlled at the corresponding positions and orientations. Similarly, the condition number of the A matrix provides an indication whether the magnets can be stably controlled without needing excessive coil currents.

In general, when the separation distance between the two levitated magnets is sufficiently large the interaction between them is expected to be negligible, as each magnet would be supported and stabilized by the coils in its own neighborhood only and there would be no coils which produce significant forces and torques on both magnets at the same time. These conditions are expected to be valid for magnet separation distances of 80 mm or more.

As the levitation magnets approach closer, the currents in the coils located between the magnets will begin to produce significant actuation forces on both magnets. These forces and torques on both magnets are represented in the transformation matrix of equations (1) and (2) so the necessary coil currents to lift and stabilize both magnets can still be calculated at each control update. These conditions are expected to be observed for magnet separation distances of 75 mm or less.

At still closer separation distances, the magnetic forces produced between the two magnets directly become significant and may be compensated by feedforward terms in the controllers of each magnet. According to Fig. 2, these forces are a small fraction of 1 N at horizontal separation distances of 50 mm or more, but they increase from approximately 0.5 N to 5 N as the separation distance between the magnets decreases from 25 to 5 mm. After accounting for gravity and interaction forces between magnets, the rigid-body dynamic model of each magnet's motion is

$$m\ddot{x} = F_c + F_g + F_m, \tag{3}$$

$$I\dot{\omega} + \omega \times (I\omega) = T_c + T_m, \tag{4}$$

for a levitated magnet with mass m, moment of inertia I, position x, angular velocity ω, gravity force F_g, coil forces F_c and torques T_c, and magnet interaction forces F_m and torques T_m. Magnet interaction forces and torques can be precalculated as described in Section III.A and shown in Figs. 2 and 3.

IV. IMPLEMENTATION

The properties and dimensions of the two NdFeB disk magnets used in the levitation system are given below.

Diameter	19.05 mm
Thickness	6.35 mm
Magnetization	N42

The magnets were obtained from from K&J Magnetics Inc. Three infrared LEDs are attached to each magnet to enable rigid-body position tracking. The LEDs are arranged in an equilateral triangular configuration with a separation distance of 43 mm and centered on each magnet.

The magnet motion tracking system is the Optotrak Certus from Northern Digital Inc. with smart markers wired together in series on each levitated magnet platform. The wired connection to the markers on each platform is lightweight and compliant. Wireless operation of the smart markers is also possible, but a battery to supply the LED power must be carried on each platform with a small electronic circuit board to synchronize the strobing of the individual LEDs with the motion tracker so that they can be uniquely distinguished for tracking.

The motion tracker is mounted directly over the coil array at a separation height of 1.8 m and oriented downwards so that the tracked LEDs are near the center of its sensing range. With three LED markers on each levitated magnet for a total of 6 markers, a sensor update rate of 570 Hz is possible with this motion tracker. The repeatability of the motion tracking for individual markers is approximately 0.01 mm.

The 22 coils are arranged in 4 rows of 5, 6, 6, and 5 in a close hexagonal packed configuration as shown in Fig. 4. The dimensions and parameters of each coil are listed below.

Outer Diameter	25 mm
Inner Diameter	12.5 mm
Height	30 mm
Windings	1000
Wire Gauge	26 AWG
Resistance	8.0 Ohm

The coils are wound on copper cores for heat dissipation and are screwed to a 12.5 mm aluminum plate. Each coil current is limited to ±4.0 A to avoid overheating. 4212Z DC Brush Servo Amplifiers from Copley Controls Inc. are used as current amplifiers to drive each actuation coils. Three PST-075-10 power supplies from Copley Controls Inc. are used to supply 75 VDC to the coil amplifiers, as each power supply can drive up to 8 of the amplifiers.

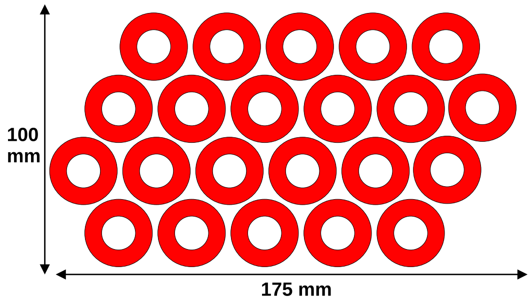

Fig. 4. Coil arrangement for two magnet levitation

Fig. 5. Two magnets levitated independently with parallel orientation by single coil array

The PD2-AO-32/16 analog output PCI card from United Electronic Industries is used to supply the 22 analog voltage command inputs to the coil amplifier boards. The motion tracking sensor interface and all control computations are performed on a Linux PC with a real-time, low latency, pre-emptive operating system kernel. The control executable is programmed in GCC C/C++ language. LAPACK matrix computation software is used directly to find the pseudoinverse of the coil current to force and torque transformation matrix of equations (1) and (2) at each control update using the *dgels* function. The computation time of these operations is not a limitation on the update rate of the system, so the system operates at the maximum update rate of the motion tracking.

Proportional-derivative digital feedback control is implemented for each degree of freedom of the two levitated magnets. A constant feedforward term is added to the control of vertical position to compensate for gravity, and feedforward terms are added to the control of horizontal position to compensate for the direction and magnitude of the modeled interaction forces between magnets as shown in Fig. 2.

V. RESULTS AND DISCUSSION

The proportional-derivative (PD) control gains used to control the position and orientation of the two magnets are shown below.

	proportional	derivative
translation	0.2 N/mm	1425 N/mm/s
rotation	2.0 Ncm/rad	28500 Ncm/rad/s

Compared to control gains used for levitation of a single magnet, the proportional and derivative gains for translation control were reduced to avoid excessive vibration of the levitated magnets. Feedforward terms were added to the position controllers to counteract the gravitational force on the levitated bodies and the horizontal forces between them, using linear interpolation of the modeled data of Fig. 2 as a lookup table indexed to the nearest mm of separation between magnets.

Fig. 5 shows both magnets levitated above the coil array. Both magnets are magnetized in the same vertical direction. Each magnet is attached to a triangular blue plastic plate with three position marker infrared LEDs.

Sample results of two levitated magnet motion control are shown in Fig. 6. In this motion control trial, the first magnet was initally levitated at xyz position $(20.0, 35.1, 10.0)$ and the second magnet at $(101.5, 35.1, 10.0)$ in mm. These positions are approximately as pictured in Fig. 5. The two magnets then were given commands to move either towards or away from each other in the x direction, at constant velocities of 5.7 mm/s, in increments of 10 mm and 5 mm. Their closest approach during the trial was approximately 50 mm, from the 8th to the 12th second of the trial. During this period the edges of the plastic plates supporting the LED markers contacted each other directly, resulting in larger rotational errors as they pushed against each other. Otherwise positioning errors of the two magnets are typically 1 mm or less during levitation, while angular errors of the levitated magnet orientations are up to 5 degrees and appear to depend on the positions of the levitated magnets.

The two magnet levitation control occasionally resulted in synchronized rotational oscillations of the magnets, indicating that dynamic interaction between the control of the two magnets is insufficiently damped. The coupled rotational oscillation of the two magnets as they are brought into closer proximity with each other may also indicate that the torques generated between the magnets when they are not perfectly coplanar and vertical should also be compensated by the control system.

The horizontal forces on aligned magnets are repulsive, while the horizontal forces on magnets with opposite polarity are attractive. When the two levitated magnets are magnetized in the same direction, as in the motion trial as shown, the vertical forces from coil currents will be generated in the same direction on both magnets. Horizontal forces and rotational torques generated on the two magnets by currents in coils between the two magnets will result in forces and torques in opposite directions on each magnet because the direction to the coil from each magnet is opposite. In future work, the two magnets will be levitated with opposite magnetization polarities, to evaluate whether this configuration

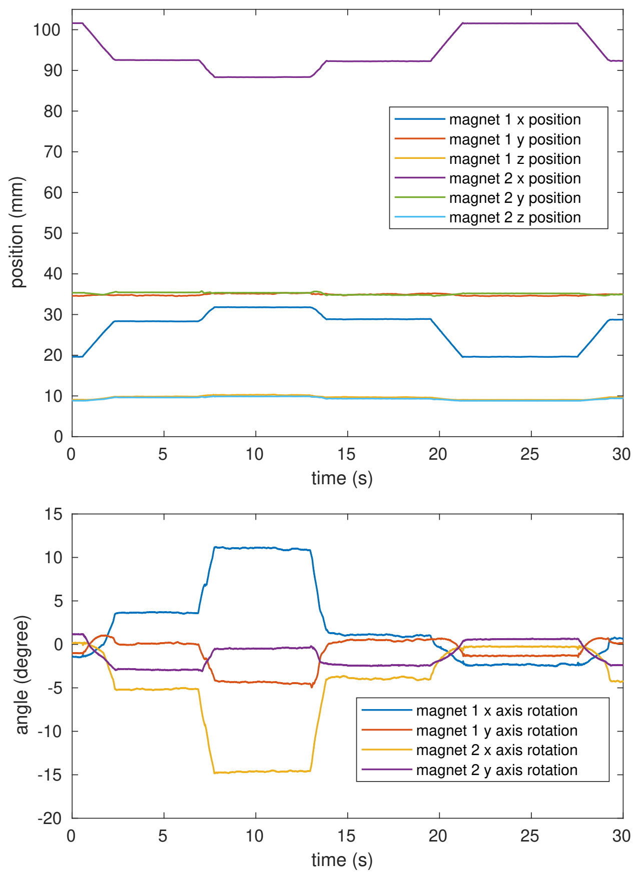

Fig. 6. Two magnet motion trajectories with same polarity

affects the stability of the two-magnet levitation dynamics.

VI. CONCLUSIONS AND CURRENT WORK

The results given here are a first demonstration and proof of concept of the idea of levitating two magnets with a single coil array and shared motion ranges. The methods used are expected to be extendable to greater numbers of coils and magnets. Three levitated magnets would introduce the possibility of three-finger force closure grasps of irregularly shaped objects.

With our present hardware, the motion tracking update rate imposes the most significant limitation on tracking more than two rigid bodies. A third levitated magnet would require three additional position marker LEDs for rigid-body motion tracking. These additional tracked LEDs would limit the motion tracking update rate to 418 Hz or less, as the maximum update rate of the Optotrak Certus motion tracker with smart markers is $4600/(2+N)$ Hz for N LED markers. The stability and accuracy of the levitation controller has previously been found to be severely limited for update rates below approximately 450 Hz.

We plan to improve the stablity of the multiple magnet levitation system by introducing additional damping terms into the levitation control laws to limit the coupled, synchronized oscillations that are observed to occur when the levitated magnets approach each other more closely. We will also introduce a more complete model of the magnetic forces and torques between the levitated magnets. The presently used model only accounts for horizontal forces between magnets when the magnets are on the same horizontal plane and their magnetization axes are parallel and vertical. A complete model will include all forces and torques generated between two magnets depending on their relative positions and orientations in all directions, and may lead to improved position accuracy and stability when the magnets are in proximity to each other.

Finally, the design and control parameters should be better tuned and optimized overall for the multiple magnet levitation system. A careful recalibration and validation procedure should be undertaken to confirm that the measured forces and torques correspond to the electromagnetic force models. As for the magnet parameters, it is likely that magnets with greater mass and moments of inertia would lead to improved stability in levitated motion control because the reduced accelerations and slower reaction times of the magnet positioning control could be more easily stabilized with the limited update rates of our present motion tracking system.

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