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# Magnetic Levitation with a Planar Array of Iron Core Cylindrical Coils

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Magnetic levitation systems with large air gaps and large ranges of motion in all directions can be realized using planar arrays of cylindrical coils, a real time motion tracking system, and feedback control of each degree of freedom in 3D rigid-body motion [1] [2]. These non-contact, frictionless motion systems have potential applications in haptic interfaces, displays, precision manipulation, and medicine. Example systems are shown in Fig. 1. Stable precise control relies on an analytic, numerical, or experimental model of the forces and torques between each magnet and coil with a given current according to their relative position and orientation. At each sensing and control update, the transformation matrix between the coil currents and the total force and torque on the levitated body is calculated, and its pseudoinverse is used to find the optimal set of currents to generate the force and torque for feedback control. This control method relies on principles of linearity and superposition for force and torque generation from coil currents.

When coils with iron cores are used, actuation forces and torques are increased by many times relative to nonferrous cores, but the linearity and superposition assumptions are potentially invalid due to magnetic saturation effects and variations in iron core magnetization produced by other coil currents and magnets in close proximity. The novelty of this work is that we investigate these nonlinear and nonsuperposition effects to find limitations on the coil currents and coil and magnet positions so that standard levitation methods may be used while considering these effects as disturbances. Fig. 2 shows example effects of nonlinearity, where the combination of low magnet heights and low currents produces downward forces due to coil core magnetization from the magnet, and high currents produce saturation effects in generated forces. Worst-case force generation errors due to core magnetization from neighboring coils were found to be less than 5% for coil axis separations greater than 30 mm and coil currents under 2.0 A. Experimental motion control results are shown in Fig. 3 for seven 25x25 mm coils with 8 mm iron cores and 35 mm axis separations and a 19.05x6.35 mm levitated magnet with LED markers, as shown in Fig.4.

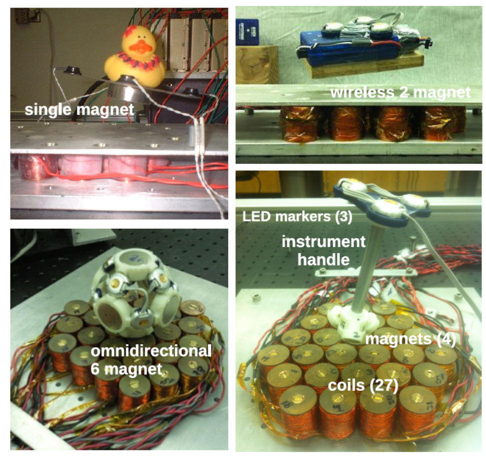


Fig. 1. Previous levitation systems with variable numbers of coils and magnets

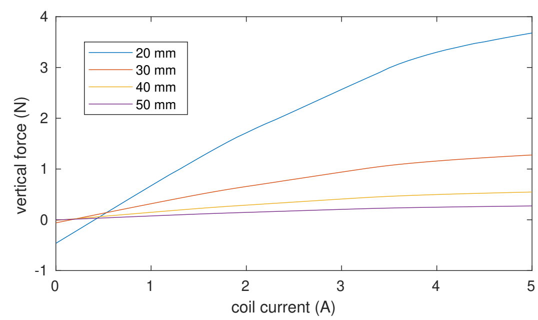


Fig. 2. Coil current to vertical force at various magnet heights with iron core coil and 6.35 mm magnet

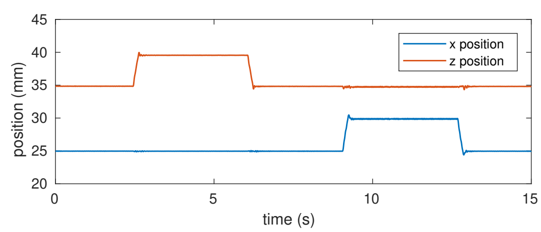


Fig. 3. Motion control of magnet levitated by iron core coils

Fig. 4. Levitated magnet with iron core coils

## REFERENCES

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[2] ——, "Magnetic levitation over large translation and rotation ranges in all directions," *IEEE/ASME Transactions on Mechatronics*, vol. 18, no. 1, pp. 44–52, 2013.

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