Large Motion Range Magnet Levitation using a Planar Array of Coils

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Abstract—We have formulated a method and implemented a device for magnetic levitation with a translation range which is at least twice as large as the dimensions of the levitated body in all directions. The motion range can be extended to any distance in the horizontal plane by adding more coils to the actuator array, and the rotation is potentially unlimited in all directions.

I. INTRODUCTION AND BACKGROUND

Magnetic levitation systems can provide many advantages for manipulation [1], fine positioning [2][3], and haptic interaction [4][5], as friction and hysteresis are eliminated and all six degrees of freedom (DOF) in translation and rotation are provided by a single levitated moving part. Existing systems [6][7] typically have ranges of motion which are limited however to a small fraction of the dimensions of the levitated body in most or all directions, and to rotation angles of less than 20 degrees. A large range of motion levitation system for small magnets with uncontrolled rotation is described in [8]. Spherical motors [9][10] control spherical orientation using magnets and coils, but without levitation.

Our system controls both position and orientation. A small range-of-motion setup is described in [11] and a redundant control setup with a large range of motion in [12].

II. METHOD

To calculate the vector transformation between coil currents \( I \) and the force and torque \( F \) generated on the levitated magnets for any given magnet position, we first measure the horizontal force \( u(r, z) \), vertical force \( v(r, z) \), and tilting torque \( w(r, z) \) on a single disk magnet from a single coil current over a sampled range of magnet levitation heights \( z \) and magnet and coil axis horizontal offset distances \( r \) to obtain the data shown in Fig. 1, using motion stages and a six-axis force-torque sensor shown in Fig. 2. Because the forces and torques generated by each coil current are proportional and independent, the total force and torque generated by all the coils together can be represented as linear matrix transformation \( \mathbf{F} = \mathbf{A} \mathbf{I} \). The Moore-Penrose pseudoinverse \( \mathbf{A}^+ \) of \( \mathbf{A} \) [13][14] is used to calculate the coil currents \( \mathbf{I} = \mathbf{A}^+ \mathbf{F} \) with the lowest sum of squared currents for levitation control, provided that the number of coils is greater than or equal to the number of DOF controlled.

The force/torque and current vectors for single magnet levitation leaving the yaw rotation uncontrolled are given by:

\[
\begin{bmatrix}
    f_x \\
    f_y \\
    f_z \\
    \tau_x \\
    \tau_y 
\end{bmatrix} =
\begin{bmatrix}
    i_1 \\
    i_2 \\
    i_3 \\
    \vdots
\end{bmatrix},
\]

and the transform matrix can be calculated as:

\[
\mathbf{A} =
\begin{bmatrix}
    \cos(\theta_1)u(r_1, z) & \cos(\theta_2)u(r_2, z) & \cdots \\
    \sin(\theta_1)u(r_1, z) & \sin(\theta_2)u(r_2, z) & \cdots \\
    v(r_1, z) & v(r_2, z) & \cdots \\
    -\sin(\theta_1)w(r_1, z) & -\sin(\theta_2)w(r_2, z) & \cdots \\
    \cos(\theta_1)w(r_1, z) & \cos(\theta_2)w(r_2, z) & \cdots 
\end{bmatrix},
\]

where \( z \) is the magnet levitation height, and \( r_1 \) and \( \theta_i \) are the horizontal distances and directions from the center of the coil \( i \) to the center of the magnet. A single disk magnet can only be controlled in 5 DOF; the yaw of the magnet cannot be controlled due to rotational symmetry and the disk is allowed to rotate freely. The rotational symmetry of the coils and magnets simplifies the force and torque generation model since the magnitudes of the forces and torques depend only on the radial distances \( r_i \) and not on the orientations of the coils or magnets or their offset direction.

III. LEVITATION TRIALS

Our present system uses an array of 10 cylindrical coils of 25 mm diameter, 25 mm height, and 1000 windings.
IV. CONCLUSIONS AND FUTURE WORKS

In our magnetic levitation system, all coil currents generate forces and torques on the same magnet or magnets, rather than using separate sets of magnets and coils to control each DOF of the levitated body. This levitation method can provide a range of motion many times larger than the dimensions of the levitated body, but a detailed model of the forces and torques generated by each coil as a function of magnet position is required, which can be obtained by direct measurement with motion stages and a force-torque sensor.

We are currently configuring motion stages to measure coil forces and torques as a function of magnet orientation as well as position, to potentially increase the stable rotation range to 360 degrees in all directions. Next, we plan to develop the present system for haptic interaction using a levitated mouse with 3-D force and torque feedback.

V. ACKNOWLEDGEMENTS

The authors gratefully acknowledge the assistance of Ji Ma in the optical motion tracker interface programming and Kendall Kido in the preparation of the video.

REFERENCES