Dynamic Inversion Enables External Magnets to Concentrate Ferromagnetic Rods to a Central Target

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Supporting Information

Materials and Methods
As mentioned in the main text, two experimental systems were developed: a one-dimensional system capable of repelling rods in a single direction, and a two-dimensional system capable of repelling rods in four directions. The one-dimensional system was used for verification of the ability of the dynamic magnetic inversion technique to invert the magnetic potential energy surface and therefore push the rods. The two-dimensional system was to demonstrate the ability of the dynamic magnetic inversion technique to concentrate and focus rods to a central target.

1-D System: To verify the dynamics of repelled rods, we first created a one-dimensional magnet system that was able to repel and image ferromagnetic rods. This one-dimensional (1-D) push system used cobalt rods (that were 200 µm long and 200 nm in diameter from PlasmaChem GmbH, Cat. Nr. PL-CoW200) submerged in water and held within a glass tube. Around this glass tube, we wound two sets of coils: the polarizing and gradient coils (see Fig. S1A). When the polarizing coil was fired, a uniform magnetic field was produced within the 3 mm wide sample region. When the polarizing coil acted alone, the uniform field oriented the particles along the direction of the polarizing magnetic field. Once the polarizing coil was deactivated and the gradient coil was fired (Fig. S1B), a non-uniform magnetic field was created that was stronger towards the left side of the sample region, and the particles moved to the right (Fig. S1C), at a speed of 19 microns/second. When the gradient coil acted alone (i.e., without a prior polarizing pulse), the particles moved to the left (i.e., toward the gradient coil).

The 1-D push system has the following specifics: The polarizing coil consisted of two 1.7 cm wide segments of 100 turns of 30 American wire gauge magnet wire (RadioShack 278-1345) wrapped around a 6 mm diameter tube. The gradient coil was also 100 turns of the same magnet wire wound on-top of one half of the polarizing coils. Two high-power pulse generators (Velonex model 360) provided power to each coil at a maximum voltage of 2.5 kV and 11 A of current. Fig. S2A details the circuit diagram for the connection of the high-power pulse generator to the gradient and polarizing coils. A signal generator (BNC model 500B) externally triggered each pulse generator allowing for the pulse duration to be varied between 1 and 1000 µs with a 1% duty cycle. A USB digital microscope (Celestron model 44302-A) was used to gather a video of the rods’ dynamics.
**Fig. S1**: Set-up schematic and results for 1-D dynamic magnetic inversion. A) Experimental set-up. The polarizing coils (purple) were two identical coils designed to create a uniform magnetic field within the sample area (hashed area in center). The gradient coil (green) was wound on only one side and produced a magnetic gradient within the sample region. B) Pulse sequence element used at 1% duty cycle that generated a push-force in the rightward direction acting upon the cobalt rods. C) Snapshots showing cobalt rods being pushed away from the gradient coil (located on left side of the image) at a speed of 19 µm/s ± 10 µm/s.

**2-D System Specifics**: The 2-D push experimental system has two pairs of polarizing coils for the x- and y-directions, and four gradient coils for +x, +y, -x, and -y. All coils surround a 25 mm x 25 mm sample region (see Fig. 5). To create a strong field intensity and gradient, the gradient coils were wound around a two centimeter diameter tube 120 times and placed next to the center region. The gradient coils were powered with the same high power pulse generator as for 1-D pushing, but with an additional module (Velonex V-1885) added that converted the generator’s output to supply 400 V at 66 A. To create the uniform field, the polarizing coils were wound around a 5 cm square structure forty-four times. The pulse generator for the polarizing coils remained unchanged from the 1-D dynamic magnetic inversion case and provided a maximum current of 11 A. All coils used 28 American wire gauge magnet wire (TEMCo model MW0213).

A Matlab (from MathWorks) graphical user interface (GUI) created on a Windows computer was designed to control a Phidget microcontroller (Phidget Interface Kit 0/16/16, P/N 1012) and the same BNC signal generator as used for 1D magnetic inversion case. The Phidget board controlled the current path by flipping a series of high voltage relays (Gigavac GH1). By adjusting which relays were turned on, current would pass through a given coil, allowing for a particular movement axis to be selected (see Fig. S2B for the circuit diagram). The circuit diagram shows a representative schematic for one gradient coil. The system had four such circuits each connected to the common voltage source and ground as appropriate. A non-connected port was located on one relay of the gradient coils so that the mutual inductance of the inoperative gradient coils did not generate current within the coil and interfere with proper system function.

The GUI was able to completely dictate all aspects of the magnetic field except for the current level, which is controlled manually by adjusting the high-powered pulse generator voltage. Parameters controllable through the GUI included: polarizing magnetic field direction (+x, +y, -x, and -y), the active gradient coil, the direction of the gradient coil’s magnetic field, the pulse sequence including the delay and width of each pulse, and the duty cycle of the pulse sequence. The GUI could then create a repulsion or attraction force in any of the four directions with any magnetic field alignment.
Fig. S2: Circuit diagram for the two experimental systems. A) Diagram for the gradient and polarizing coil relays used in the one-dimensional system. B) Diagram for the gradient and polarizing coil relays used in the two-dimensional system. Each relay is controlled by the Phidget controller.