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Sat-Mo-Po.01-06: A Novel Two-Dimensional Magnetic Driving System using Maxwell Coils and a Halbach Array

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Microrobots are increasingly being applied in bionics and medicine, demonstrating significant potential in minimally invasive surgery and targeted drug delivery. Among them, magnetic microrobots have attracted considerable attention, driven by the interaction between external magnetic fields and built-in permanent magnets. This enables the separation of the driving system from the robot body, allowing for a smaller size, more flexible movement, and contactless control.

For magnetic microrobots moving in a two-dimensional plane, microrobot actuation requires bidirectional gradient magnetic fields and a controlled uniform magnetic field. The gradient fields generate a propulsive force, while the uniform field generates a magnetic torque to rotate the microrobot. Traditionally, electromagnetic coil systems, such as Maxwell coils or Helmholtz coils, have been used to generate these fields. In previous works, two-dimensional planar magnetic field control systems typically used two pairs of Maxwell coils and two pairs of Helmholtz coils arranged vertically. However, such an 8-coil system suffers from high energy consumption, complex configuration, and significant challenges in development and optimization.

To address these limitations, we propose a novel two-dimensional magnetic driving system that comprises only one pair of Maxwell coils alongside a hard-magnetic Halbach array. The first part, the Maxwell coils, can generate an axial gradient field as well as a radial concomitant gradient field in their central plane. Although the concomitant gradient field is generally considered detrimental, its symmetry can still be utilized to replace the two pairs of axial Maxwell coils by producing bidirectional gradient magnetic fields. This allows for the pushing of magnetic microrobot along its magnetization direction through the gradient magnetic force. The second part is the ring-shaped Halbach array, which consists of 32 small magnets and is driven by a servomotor. It serves as an effective alternative to Helmholtz coils to generate a controllable uniform magnetic field with reduced energy consumption. This uniform field aligns the magnetization direction of the microrobot with the desired orientation through magnetic torques. Then the combination of the pushing forces generated by the Maxwell coils and the torques produced by the Halbach array enables flexible movement of the microrobot in the two-dimensional plane.

To validate the performance of our proposed device, we model it using finite element simulation software to verify the theory and method outlined above. In the model, we optimize the parameters of the Maxwell coils and the Halbach array to ensure the synergistic action of the gradient and uniform fields, while minimizing mutual interference and maximizing the effective control range of the entire coupled system. We design the effective control area to have a radius equal to 9% of the Maxwell coils' radius and a height equal to 15% of the distance between the two coils. In this control area, the magnetic field generated by the Maxwell coils is approximately 10% of the size of the Halbach array, while the magnetic field gradient generated by the Halbach array is about 10% of the size of the Maxwell coils. Finally, we place a permanent magnet in the area and analyze its force and motion characteristics. The simulation results demonstrate the high efficiency, stability, and flexibility of the proposed magnetic driving system, enabling precise manipulation of microrobots in the two-dimensional plane.

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