# Supplemental Materials for

# A theoretical investigation of the ability of magnetic miniature robots to exert forces and torques for biomedical functionalities

Yuxuan Xiang,[1] and Jiachen Zhang[1]

[1]*Department of Biomedical Engineering, City University of Hong Kong,*
*Hong Kong SAR, China*

## CONTENT

## S1. Comparison of permanent magnet and electromagnetic coil as the field generator

External magnetic field can be generated through permanent magnets and electromagnetic coil systems. Electromagnetic coil systems that have been evaluated in this work are either single coil which is valid for Eq. (3) or the standard electromagnet OctoMag. We ensure that the electromagnetic coil systems evaluated in our work are also suitable for dipole model. Both the magnetic flux density $\mathbf{B}_2$ generated by either permanent magnet or electromagnet can be calculated through Eq. (6).

In addition to single magnetic source, systems consist of multiple permanent magnets [1] or electromagnetic coils [2] have been reported to achieve more powerful and controllable actuation. A linear addition of magnetic fields based on superposition principle can be used to calculate the total magnetic flux density $\mathbf{B}_{total}$ of a system composed of $N$ magnetic sources:

$$\mathbf{B}_{total}=\sum_{i=1}^{N}\mathbf{B}_{2i}=\sum_{i=1}^{N}\frac{\mu_0}{4\pi}\left[\frac{3\mathbf{r}_i(\mathbf{r}_i\bullet\mathbf{m}_{2i})}{r_i^5}-\frac{\mathbf{m}_{2i}}{r_i^3}\right]$$

However, these systems with multiple magnetic sources can not efficiently and significantly increase the magnetic field due to vector cancellation in space. Meanwhile, the multiple source systems, especially most electromagnets, are applied in an enclosed and limited workbench and occupy significantly large space which limits their potential applications. Therefore, we chose to evaluate the ability to generate magnetic flux density and magnetic field gradient of a single magnet in our work. The comparison also consider the volume values of various magnets which are associated with the available working area of robots and actuating distance.

A single coil of OctoMag has a dimension which is 14.6 times of the volume of a reported permanent magnet [3] but has a 28 times smaller magnetic moment. By considering an overly large space of peripheral and a limited operating workbench ($20\ mm\times 20\ mm$), permanent magnets with stronger ability to generate magnetic field and superior flexibility to be employed in wide range of working distances, are more ideal field actuators in our model to investigate the maximum attainable forces and torques. Similar simulation results have been presented in [4], permanent magnets have the potential to produce significantly higher field strengths and gradients than electromagnets.

## S2. Selection of permanent magnet parameters

Previous research that utilize permanent magnets tend to report their magnetic properties in various ways:

1. Geometry size of permanent magnet.
2. Grades of NdFeB (e.g., N42, N52).
3. Magnetization.
4. Magnetic moment.
5. Residual flux density.

Information (1) and (2) are most frequently reported in various research. However, magnetization or magnetic moment are more intuitive parameters than grades of NdFeB in our work. In addition to geometry size, if grades are the only parameter that have been reported, we assume a maximum relative residual flux density $\mathbf{B}_r$ for each grades from *K&J Magnetics, Inc.* With a known $\mathbf{B}_r$, the magnetic moment $\mathbf{m}_2$ can be calculated as:

$$\mathbf{m}_2 = \frac{\mathbf{B}_r V_m}{\mu_0}$$

Permanent magnets with different geometries, sizes, and magnetic properties have been evaluated and compared in **Table S2**. Custom NdFeB magnet with overly large size (red line) supposes to cause significant error of dipole model due to small ratio of working distance to body length. Meanwhile, such dramatically powerful custom magnets are extremely costly and likely to cause dangers during manipulation. Therefore, a commercial cuboidal NdFeB with the largest available non-custom side length of 50 mm from *K&J Magnetics, Inc.* (green line) is considered to be the most ideal magnetic field generator in our work. This N52 grade NdFeB magnet has a magnetic moment of 131 $\text{Am}^2$ and will not result in differences of orders of output force and torque magnitude compared with other customized NdFeB magnet with slightly larger size (blue lines). We choose the most commonly used large NdFeB magnet to ensure that other researchers can easily reproduce our simulation results.

In order to investigate the maximum ability of miniature robots to exert forces and torques, this most ideal magnetic material NdFeB with a magnetization of $1.05 \times 10^6$ A/m has been applied for both external source for field actuation and internal material for magnetic robots. More specifically, the magnetic components of the miniature robots are considered to have the same magnetic property as the external permanent magnet in dipole model assuming no significant difference in magnetic properties with different magnets' size [5].

## Table S1. External magnetic actuators applied to miniature robots

| *Size scale (m)* | *Characteristic Length* | *Robot Shape* | *Field Generation (Actuating Position)* | *Reported Magnetic Flux Density and Gradient* | *Maximum Force and Torque* |
|---|---|---|---|---|---|
| $10^{-7}$ | 500 nm [30] | Swarm (single) | Electromagnets (Center) | $\mathbf{B}$= 10 mT | $\mathbf{F}= 1.15\times10^{-13}$ N *<br>$\mathbf{T}= 3.82\times10^{-15}$ Nm * |
| $10^{-6}$ | 5 μm [27] | Bead | Electromagnets (Center) | $\nabla\mathbf{B}$= 15.36 T/m | $\mathbf{F}= 1.20\times10^{-10}$ N |
| $10^{-5}$ | 10 μm [29] | Bacteria flagella | Electromagnets (Center) | $\mathbf{B}$= 15 mT | $\mathbf{F}= 6.77\times10^{-12}$ N<br>$\mathbf{T}= 5.28\times10^{-17}$ Nm |
|  | 38 μm [28] | Bacteria flagella | Electromagnets (Center) | $\mathbf{B}$= 2 mT | $\mathbf{F}= 3\times10^{-12}$ N<br>$\mathbf{T}= 4.30\times10^{-17}$ Nm |
| $10^{-4}$ | 500 μm [9] | Needle | Electromagnets (Center) | $\mathbf{B}$= 15 mT<br>$\nabla\mathbf{B}$= 0.80 T/m * | $\mathbf{F}= 2.65\times10^{-6}$ N<br>$\mathbf{T}= 5\times10^{-8}$ Nm * |
| $10^{-3}$ | 1.8 mm [23] | Cylinder | Electromagnets (Center) | $\mathbf{B}$= 35 mT<br>$\nabla\mathbf{B}$= 0.80 T/m * | $\mathbf{F}= 1\times10^{-4}$ N<br>$\mathbf{T}= 1.10\times10^{-5}$ Nm * |
|  | 2 mm [19] | Needle | Permanent magnet (70 mm) | $\mathbf{B}$= 9.62 mT *<br>$\nabla\mathbf{B}$= 0.41 T/m * | $\mathbf{F}= 5\times10^{-5}$ N<br>$\mathbf{T}= 1.15\times10^{-6}$ Nm * |
|  | 2 mm [9] | Needle | Electromagnets (Center) | $\mathbf{B}$= 15 mT<br>$\nabla\mathbf{B}$= 0.79 T/m * | $\mathbf{F}= 5.40\times10^{-5}$ N<br>$\mathbf{T}= 1.03\times10^{-6}$ Nm * |
|  | 2.7 mm [9] | Needle | Electromagnets (Center) | $\mathbf{B}$= 15 mT<br>$\nabla\mathbf{B}$= 0.37 T/m * | $\mathbf{F}= 2.30\times10^{-4}$ N<br>$\mathbf{T}= 9.22\times10^{-6}$ Nm * |
|  | 3.7 mm [14] | Cuboidal | Electromagnets (Center) | $\mathbf{B}$= 50 mT<br>$\nabla\mathbf{B}$= 0.35 T/m * | $\mathbf{F}= 1.56\times10^{-6}$ N *<br>$\mathbf{T}= 2.10\times10^{-7}$ Nm * |
|  | 6 mm [16] | Screw | Electromagnets (150 mm) | $\mathbf{B}$= 2.80 mT | $\mathbf{T}= 1.26\times10^{-4}$ Nm |
|  | 6.4 mm [13] | Helical swimmer | Permanent magnets (75 mm) | $\mathbf{B}$= 31.20 mT<br>$\nabla\mathbf{B}$= 0.83 T/m | $\mathbf{F}= 1.80\times10^{-3}$ N *<br>$\mathbf{T}= 6.86\times10^{-5}$ Nm * |
|  | 7.5 mm [31] | Hexagon | Permanent magnet (8 mm) | $\mathbf{B}$= 130 mT<br>$\nabla\mathbf{B}$= 29.31 T/m * | $\mathbf{F}= 8.90\times10^{-2}$ N (Lower shell)<br>$\mathbf{T}= 2.61\times10^{-4}$ Nm (Upper shell) |
|  | 8.8 mm [26] | Torsion spring | Electromagnets (Center) | $\mathbf{B}$= 20 mT | $\mathbf{T}= 3\times10^{-4}$ Nm |
| $10^{-2}$ | 10 mm [20] | Catheter | Permanent magnet (132 mm) | $\mathbf{B}$= 80 mT<br>$\nabla\mathbf{B}$= 1.75 T/m | $\mathbf{F}= 5.63\times10^{-5}$ N *<br>$\mathbf{T}= 2.81\times10^{-6}$ Nm |
|  | 14 mm [15] | Helical screw | Electromagnets (Center) | $\mathbf{B}$= 14 mT<br>$\nabla\mathbf{B}$= 12.40 T/m | $\mathbf{F}= 1.80\times10^{-4}$ N<br>$\mathbf{T}= 1\times10^{-4}$ Nm |
|  | 15 mm [25] | Scissor | Electromagnets (Center) | $\mathbf{B}$= 20 mT | $\mathbf{F}= 3.50\times10^{-2}$ N<br>$\mathbf{T}= 5.02\times10^{-4}$ Nm * |
|  | 20 mm [21] | Catheter | Permanent magnet (50 mm) | $\mathbf{B}$= 100 mT<br>$\nabla\mathbf{B}$= 6.29 T/m * | $\mathbf{F}= 3.10\times10^{-4}$ N<br>$\mathbf{T}= 4.96\times10^{-6}$ Nm * |
|  | 20 mm [18] | Capsule | Permanent magnet (150 mm) | $\mathbf{B}$= 11.25 mT *<br>$\nabla\mathbf{B}$= 224.97 T/m * | $\mathbf{F}= 3.35\times10^{-1}$ N<br>$\mathbf{T}= 2.85\times10^{-4}$ Nm * |
|  | 21 mm [4] | Gripper | Electromagnets (Center) | $\mathbf{B}$= 20 mT<br>$\nabla\mathbf{B}$= 5 mT/m * | $\mathbf{F}= 6\times10^{-3}$ N |
|  | 22 mm [17] | Capsule | Electromagnets | $\mathbf{B}$= 16.58 mT *<br>$\nabla\mathbf{B}$= 0.99 T/m * | $\mathbf{F}= 6\times10^{-1}$ N<br>$\mathbf{T}= 1\times10^{-2}$ Nm |

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|---|---|---|---|---|---|
| | 30 mm [24] | Coil | Electromagnets (100 mm) | **B**= 1.12 mT *<br>∇**B**= 16.40 mT/m * | **F**= $6.40\times10^{-5}$ N<br>**T**= $1.85\times10^{-4}$ Nm |
| | 32 mm [22] | Cylinder | Permanent magnet (64.7 mm*) | **B**= 15.43 mT *<br>∇**B**= 0.72 T/m * | **F**= $1.43\times10^{-1}$ N<br>**T**= $1.52\times10^{-3}$ Nm |
| | 40 mm [3] | Capsule | Permanent magnets (100 mm) | **B**= 35 mT *<br>∇**B**= 1.05 T/m * | **F**= $6\times10^{-1}$ N<br>**T**= $3.60\times10^{-3}$ Nm |

Notes:

1. * denotes that this data was not directly given by the previous study, but instead it is calculated based on known parameters.
2. Reference numbers follow the order in main text in order to intuitively show the detail compared with FIG. 3.

### Table S2. Comparisons of permanent magnets as the field generators

| *Magnetic field generator* | *Geometry and size* | *Magnetic moment ($Am^2$)* | *Magnetization (A/m)* | *Magnetic field and gradient at 200mm* |
|---|---|---|---|---|
| N42-NdFeB [19] | $40\times40\times20$ mm$^3$<br>Cube | 29.36 | $9.18\times10^5$ * | $\mathbf{B}=0.73$ mT<br>$\nabla\mathbf{B}=11.01$ mT/m |
| 8 N42-NdFeB [13] | $25.4\times25.4\times25.4$ mm$^3$<br>Single cube | 16.60 | $1.01\times10^6$ * | $\mathbf{B}=0.83$ mT<br>$\nabla\mathbf{B}=4.73$ mT/m |
| N42-NdFeB [31] | $\phi60\times10$ mm$^3$<br>Cylinder | 27.90 | $9.87\times10^5$ * | $\mathbf{B}=0.70$ mT<br>$\nabla\mathbf{B}=10.46$ mT/m |
| N52-NdFeB [20] | $\phi100\times100$ mm$^3$<br>Cylinder | 906.25 | $1.15\times10^6$ * | $\mathbf{B}=22.66$ mT<br>$\nabla\mathbf{B}=339.84$ mT/m |
| N52-NdFeB [21] | $50\times50\times50$ mm$^3$<br>Cube | 131 | $1.05\times10^6$ * | $\mathbf{B}=3.28$ mT<br>$\nabla\mathbf{B}=49.13$ mT/m |
| N52-NdFeB [22] | $\phi50.8\times12.7$ mm$^3$<br>Cylinder | 20.90 | $8.12\times10^5$ * | $\mathbf{B}=0.52$ mT<br>$\nabla\mathbf{B}=7.84$ mT/m |
| N52-NdFeB [3] | $\phi50\times80$ mm$^3$<br>Cylinder | 175 | $1.11\times10^6$ * | $\mathbf{B}=4.38$ mT<br>$\nabla\mathbf{B}=65.63$ mT/m |
| N35-NdFeB [18] | $\phi60\times70$ mm$^3$<br>Cylinder with a hole | 189.82 | $9.63\times10^5$ * | $\mathbf{B}=4.75$ mT<br>$\nabla\mathbf{B}=71.18$ mT/m |

Notes:

1. * denotes that this data was not directly given by the previous study, but instead it is calculated based on known parameters.
2. Reference numbers follow the order in main text.
3. Permanent magnets marked out by red line, blue line, and green line represent overly large customized permanent magnets, slightly larger customized permanent magnets, and an ideal standard permanent magnet, respectively.

## References

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