Design of a Cylindrical Halbach Array for Portable Low-Field MRI

Team: Jessica Ritchie, Kaitlyn Jenkins, Matthew Ocando, Manpreet Singh, Weitao Wu

INTRODUCTION

- Low-field MRI is an emerging technology that offers advantages over traditional high-field MRI such as low cost, portability, and increased safety [1].
- Unfortunately, low-field MRI produces lower quality images compared with high-field scans.
- Low-field MRI is gaining popularity as research in machine learning algorithms can improve image quality as seen in Figure 1.

Image Quality From Low and High Field MRI

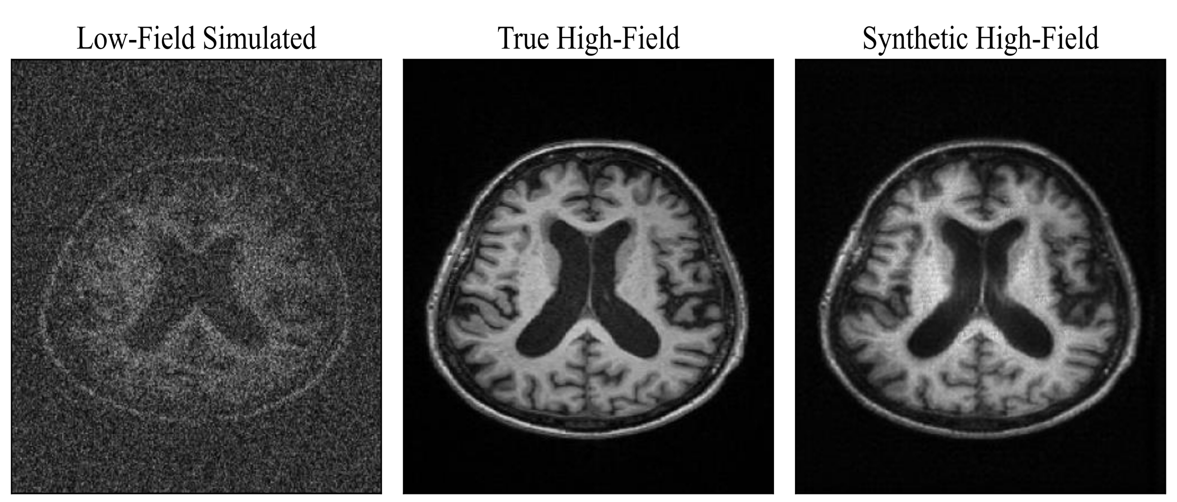


Figure 1. Low-field MRI image (left) is enhanced to a synthetic high-field MRI (right) and compared to the true high-field image (center). Image courtesy of Fernando Vega.

OBJECTIVE

To design a Halbach array for a portable low-field MRI for brain and infant scanning and determine the optimal location of each permanent magnet that maximizes the field strength and homogeneity. This requires validating the accuracy of our simulation software through analytical calculations, simulating our final design and optimizing for each permanent magnet position.

In addition, our final design must meet the following requirements:

- Bore diameter ≥ 35 cm.
- Weight ≤ 1 000 lbs.
- Length ≥ 0.5 m.
- Cost ≤ $60 000.
- We did not set a limit for field homogeneity, however we should aim for the lowest variance that can be achieved with an average magnetic field strength ≥70mT.

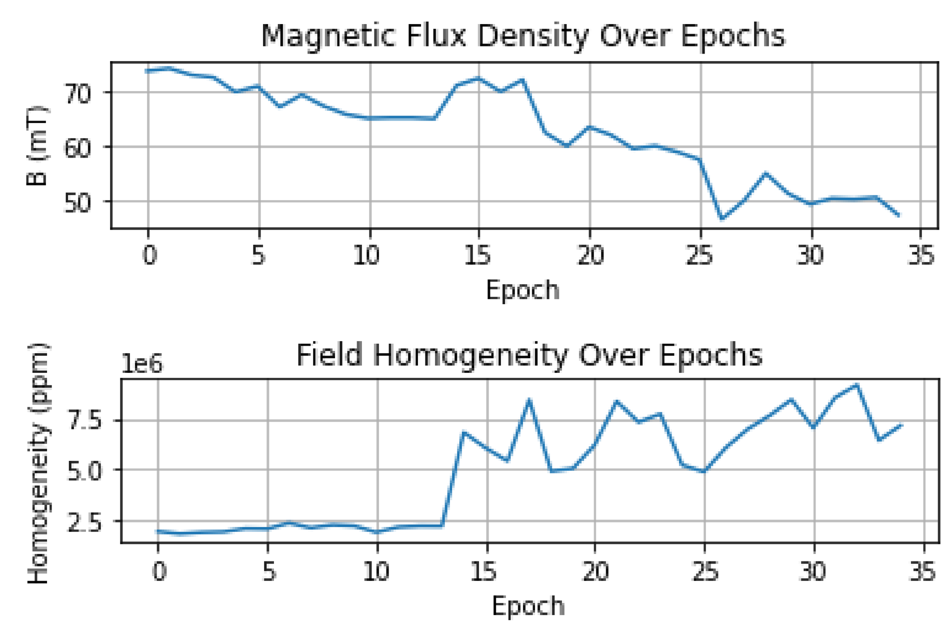
METHODOLOGY

- Analytical calculations of the magnetic field strength at various points for an individual magnet and single Halbach array were preformed using MATLAB to validate our simulations in COMSOL Multiphysics.
- COMSOL was used to simulate a single Halbach array and our final stacked ring design. A python script was written to automatically generate the final assembly in COMSOL.
- Data generated from COMSOL was analyzed using stochastic gradient descent in python to determine the optimal location and orientation of each permanent magnet to maximize field strength and homogeneity.

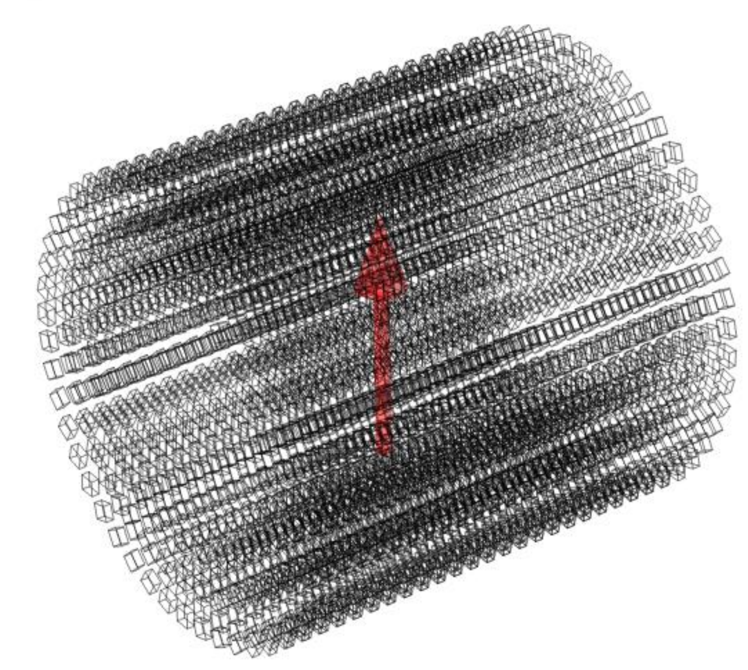
RESULTS

- N42 grade ½" x ½" x 1" magnets were selected because of their shape, size, availability, and safety considerations.
- The percent error between our analytical results and COMSOL simulations were 4.1% and 14.1% for the magnet and ring respectively. These results confirmed the accuracy of our simulation software.
- The stochastic gradient descent procedure was tested on a single Halbach array consisting of 3 concentric rings. Over 34 iterations we did not see improvement in the homogeneity as magnetic field strength was sacrificed as seen in Figure 2 image A.
- Final design used the symmetrical Halbach arrangement because our optimization did not show significant improvement by deviating from the theoretical ideal positions.

A



B



Red arrow shows the direction of magnetic field

C

Concentric Rings	Field Strength	Homogeneity
1	29.38 mT	1 319 642 ppm
2	52.80 mT	878 259 ppm
3	72.05 mT	672 842 ppm

D

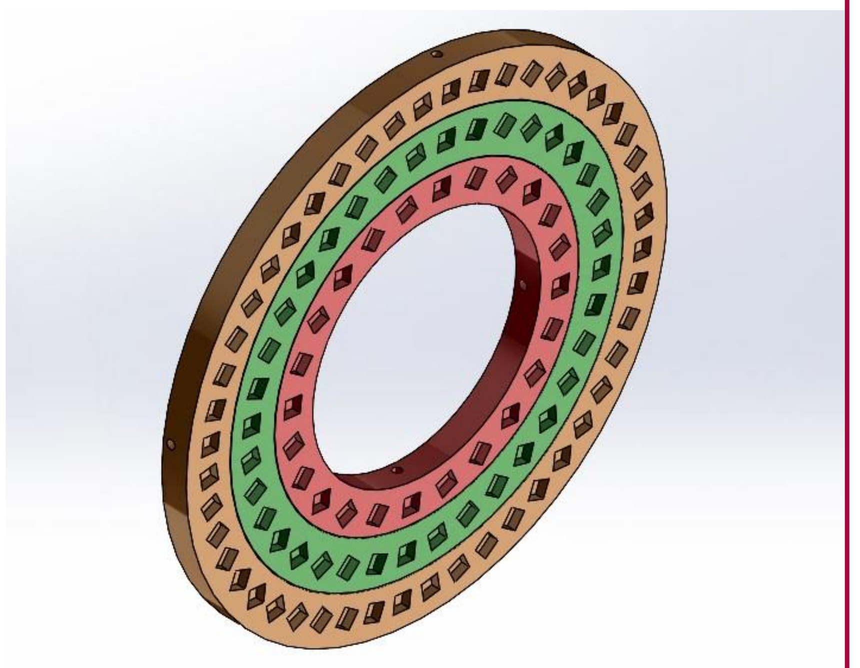


Figure 2. A Magnetic flux density and homogeneity over optimization iterations **B** Final design **C** Effect of concentric rings on field strength and homogeneity **D** 3D casing for single slice of the array.

- The desired field strength was achieved by adding concentric rings (Figure 2 image C), double stacking magnets and reducing the spacing between arrays.
- Our final design is shown in Figure 2 image B. This design achieved an average magnetic field strength of 72.05 mT with a homogeneity of 672 842 ppm.
- The arrangement contains 25 arrays of 3 concentric rings consisting of 24, 36 and 48 double stacked magnets each. The design has a bore size of 40cm and length of 74.54 cm.
- A shell for a single array was developed in Solidworks as shown in Figure 2 image D.
- The 25% scaled version of the casing was 3D printed in PLA.

DISCUSSION

Future work on this project would include:

- Further optimization of magnet arrangements to increase the magnetic field strength beyond 70mT and increase homogeneity.
- Design and manufacture the entire casing.
- Develop remaining components necessary for a functioning MRI machine.
- Machine learning techniques to improve image quality and clinical studies to assess its performance in real-world settings.

Limitations of our design include:

- The optimization stops when magnets converge.
- Double stacked magnets were approximated using ½"x1"x1" magnets.

Conclusion:

- Did not achieve significant improvements in field strength and homogeneity from optimization to warrant deviating from theoretically ideal design.
- Our final design fits within all initial constraints.
- Achieved an average magnetic field strength of 72.05mT. This demonstrates the feasibility of using permanent magnets to achieve a field strength sufficient for low-field MRI.
- Final design contains 5 400 magnets weighing a total of 365.83 lbs excluding the weight of the casing.
- The cost to purchase these magnets is approximately $31 500.

SOURCES

[1] "Portable magnetic resonance imaging of patients indoors, outdoors and at home | Scientific Reports." https://www.nature.com/articles/s41598-022-17472-w (accessed Oct. 27, 2022).

[2] A. R. Purchase *et al.*, "A Short and Light, Sparse Dipolar Halbach Magnet for MRI," *IEEE Access*, vol. 9, pp. 95294–95303, 2021, doi: 10.1109/ACCESS.2021.3093530.

[3] "K&J Magnetics: B88X0." https://www.kjmagnetics.com/proddetail.asp?prod=B88X0 (accessed Mar. 23, 2023).

ACKNOWLEDGEMENTS

Sponsor: University of Calgary BIT Lab
Sponsor Representative: Ethan MacDonald
Academic Advisor: Fernando Vega
CMC Microsystems for provision of COMSOL Multiphysics

Brain Image Team