**Development of 3D-printed Halbach Cylinder for Teaching and Research in Geomagnetism**

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***Abstract***

Strong magnetic fields are often used to characterize the magnetic mineral assemblage in rocks and sediments. Typically, these measurements are only possible in the lab, as the instruments needed to generate large fields are usually large, expensive, water-cooled electromagnets. Here we explore the use of a Halbach array, which is composed of a circular arrangement of carefully positioned magnets that additively create a stronger magnetic field in the center of the circle than that generated by any single magnet in the arrangement. The resulting field in the center of the Halbach array is homogeneous along one axis, while nulled along other axes. Such arrangements have many potential applications due to their portability; yet previous versions of the array have been expensive and/or required substantial resources to build. Here, we explore a more accessible design, constructed using 3D printing to create a rigid frame to position and hold commercially available rare earth magnets. Initially, a small hand-held ring was designed and successfully assembled to accommodate rock chip samples that could be collected in the field. A second, larger outer ring was then designed that can be rotated about the smaller ring to generate a range of adjustable fields. The ability to strongly magnetize a sample while outside in the field using a variety of user-controlled fields has many applications for paleomagnetic and environmental magnetic studies. Most smartphones contain 3-axis magnetometers that can be used to measure a sample’s magnetization after being magnetized by the Halbach array. Thus, we envision that our device could potentially be used in conjunction with a mobile app, allowing field measurements to be taken with a smartphone.

***Keywords***

***Introduction***

*Introduce/explain Halbach array properties*

Homogeneous fields are of merit in several applications. In particular, a Halbach array can be used to produce a strong field,

A Halbach array effectively

The ultimate project goal is to inexpensively construct a Halbach array with the use of 3D printing and permanent magnets in the hopes of reproducing the properties of the array in a more accessible and useful manner. Therefore, 3D printing is an attractive method of production, allowing for easy modification of an existing model for the purpose of continual refinement. Additionally, the cost and labor associated with 3D printing is minimal in comparison to other methods of fabrication. The availability of relatively strong permanent magnets The magnets chosen for the product are a compromise between strength and price; neodymium is a relatively inexpensive material, yet produces magnets with a strong magnetic field within a small size. Therefore, the combination of both materials allows for a fairly accessible final product when compared to available commercial alternatives.

The design focused on producing a configuration that can be used to take measurements portably, perhaps in the field or some such similar setting. The Halbach array is notable in that the precise orientations given by a series of equations allows for a much stronger field to be produced than each individual magnet could produce on its own. Fields as strong as a tesla can be generated, and successive concentric rings can both add to this field as well as be rotated to a specified number of degrees. This would allow for either addition or subtraction of the outer ring’s components from the produced field of the static inner ring; thereby creating both a maximum and minimum field strength. Therefore, design initially focused on the creation of a single ring of magnets, and once refined, a second ring was added to the design, with the ability to rotate the outer ring a total of 180 degrees around the inner ring of magnets.

The goal of this study is to test if a Halbach array could plausibly be created in an accessible and inexpensive manner, primarily utilizing 3D-printing as a resource.

***Methods***

The chosen magnets were treated as ideal magnets, with identical properties and produced magnetic fields. Equations modified from (Raich & Blümler, 2004) were manipulated in Excel to determine magnet position.

Each iteration of the ring’s design was created in *SOLIDWORKS 2019*. Cura was used for additional editing and for .gcode conversion. Models were printed on both Lulzbot Mini and Lulzbot Taz6 3D printers.

The strength of the magnetic field produced in each orientation was measured with three probes, an axial hall probe, transverse hall probe, and lakeshore hall probe.

As three varieties of hall probe were utilized to measure the produced field, three individual “holders” were laser cut from acrylic in order to match the specifications of each probe, as well as designed to be able to fit closely within the center of the ring for the purpose of minimizing error produced from minute shifting during measurement. This static holder, with known spacing, allowed for measurements to be plotted onto a grid, resulting in consistent three-dimensional coordinates.

***Design***

By far, the greatest time investment of this project involved the design process of the cylinder. It took several iterations to determine the features necessary for the function of the ring.

The magnets chosen for this project are cubic in shape, manufactured to be 10mm x 10mm. Composed of rare earth elements, K&J manufacturing…

Initially, a design of a ring of 8 magnets was chosen. The resulting symmetry made the ring design problematic, and as a result a design with 12 magnets was chosen. This is due both to the fact that it allowed for a more distinctive pattern as well as for the purposes of producing a stronger magnetic field. By the equations in (Raich & Blümler, 2004) a minimum inner diameter of 32.5mm was calculated, ensuring a close fit between magnets. A width of 17mm produced a ring that reasonably fit magnets in each potential rotated orientation, as well as allowing a sufficiently large inner diameter in which to put things in.

The ring itself was initially imagined as two separate parts: a bottom ring with shallow, recessed wells into which magnets could be placed, as well as an identical top ring. When these two rings were assembled, they formed a single unit that would encase the magnets and ensure permanent magnet emplacement. Each ring would be affixed either with the use of screws or designed with such a precise fit as to remain as a single unit.

After initial testing, it was determined that the magnet emplacement and the final assembly of the unit would be simpler if the unit consisted of a single ring, with deeper wells into which the magnets were placed, with several millimeters of clearance between the top of the magnet and the top surface of the Halbach ring. This eliminated simple mechanical issues present in the first design, as the rare earth magnets chosen were difficult to orient with regards to repulsion and attraction from surrounding positions. The deeper wells prevented this initial shifting of magnets during assembly of the final unit.

Trial and error produced a design for the magnet recesses with dimensions slightly smaller than the manufactured size, 9.95mm x 9.5 mm. This, when combined with the slight errors due to manufacturing processes as well as between CAD design and printing, allowed for a precise fit of the magnets into the designed recesses in the ring. Magnets could be individually removed but remained firmly in place when the assembly was overturned. This resulted in a fairly durable final product, with few concerns about careful handling.

The final product of this inner ring resulted in a ring with recessed squares, 9.95 x 9.95 mm, with 12 magnets arrayed as such.

Once the design of the inner ring was finalized, a mechanism involving a second, rotating outer ring was imagined. This ring also utilized the 10 mm x 10 mm magnets used in the construction of the smaller, inner ring. The second ring was designed to maximize the potential magnetic field produced by the addition of this outer ring, thereby minimizing empty space between magnets. Several potential ring designs were considered, and the design that compromised between magnet density and ring integrity resulted in an outer ring of 19 magnets.

A tongue-in-groove system was utilized to both connect the inner ring to the outer ring, as well as to limit the possible rotation between rings to 180°. The protrusion along the bottom of the inner ring fits into a groove designed along the base of the outer ring. To stabilize the entire unit, a base was also designed such that the integrity of the tongue would be protected, as well as to provide an easier surface for which to grasp and manually rotate the unit.

***Results***

***Discussion***

***Conclusions***

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***References***

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***Tables***

***Figures***