Design of a magnetic field mapping rover system for a neutron lifetime experiment

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Abstract

The beta decay lifetime of the free neutron is an important input to the Standard Model of particle physics, but values measured using different methods have exhibited substantial disagreement. An experiment using ultra-cold neutrons (UCNs) is planned at LANL to explore better methods of measuring the neutron lifetime. In this experiment, UCNs are confined in a magneto-gravitational trap formed by a curved, asymmetric Halbach array surrounded by holding field coils. If any defects present in the Halbach array are sufficient to reduce the local field near the surface below that needed to repel the desired energy level UCNs, loss to material interaction can occur at a rate similar to the loss by beta decay. The design of a system to map the magnetic field of the trap using a rover and computer vision-based tracking system is described here.

Background

Ultracold Neutrons (UCNs)

- Neutrons with kinetic energy <~300 neV; on the order of the gravitational potential energy of a neutron at ~1 m and μ·B with B on the order of 1 T.
- Can be easily confined by magnetic fields, gravity, and certain materials.

Neutron lifetime measurement

- Free neutrons decay to a proton, electron, and electron antineutrino with a mean lifetime around 15 min., but experiments attempting to measure this value have arrived at conflicting results.
- An experiment in development at LANL plans to explore new methods of measuring this value using UCNs.
- A Halbach array (an arrangement of permanent magnets that creates a strong magnetic field on one side of the surface) is being used to confine the UCNs in this experiment.
- Several of the >5,000 permanent magnets comprising the Halbach array have defects of various sizes. If a defect is sufficient to reduce the local field below that which is necessary to repel UCNs with energies that should be trapped, UCNs can be lost to material interactions at a rate similar to the free neutron beta decay rate, which would create a systematic shift in the lifetime measurement.

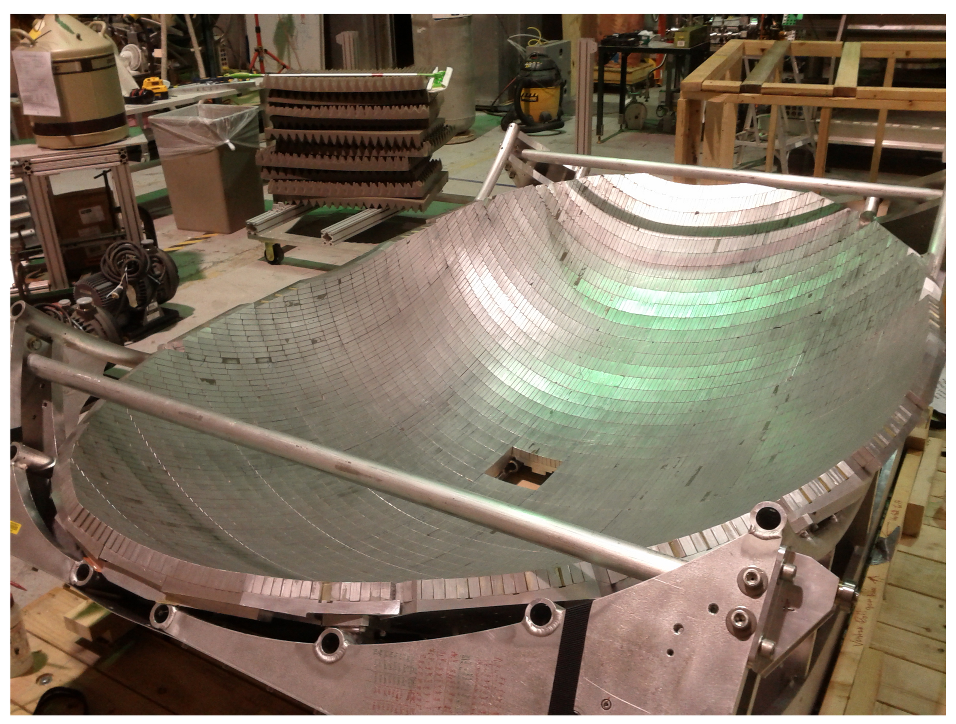


FIG. 1: The Halbach array used in the trap. The array is around 2 m by 1.5 m in size.

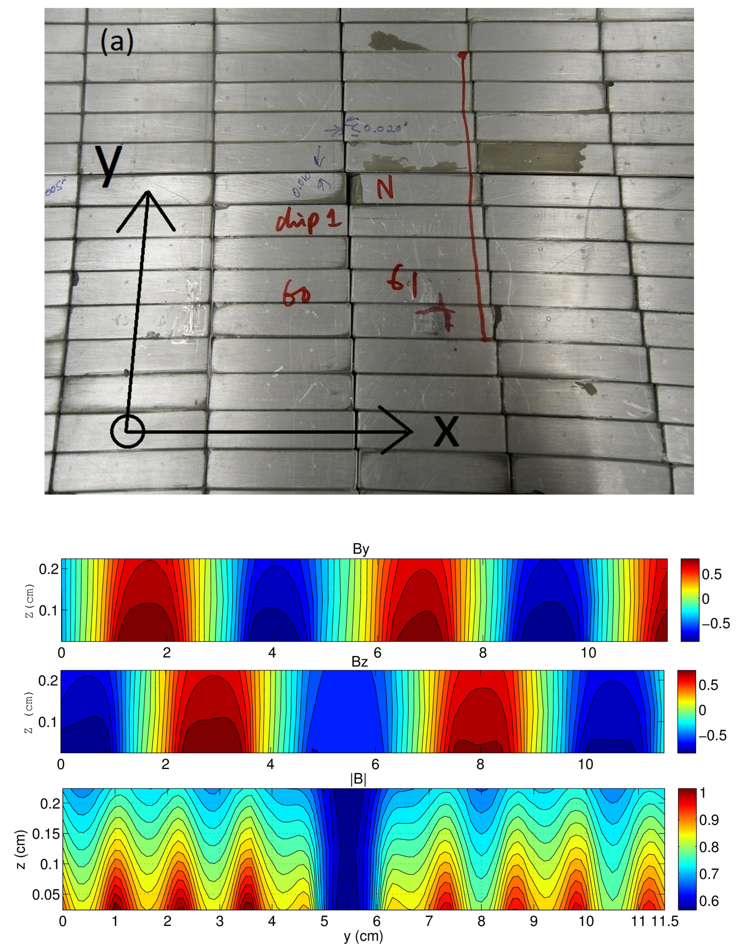


FIG. 2: Result of a magnetic field scan using over a section of the Halbach array pictured above with a defect due to a chipped magnet, which can be seen in the discontinuity in |**B**| *between y = 5 and 6 cm. This scan was performed during the construction of the array using a Hall probe mounted on an XYZ stage by collaborators at Indiana University.*

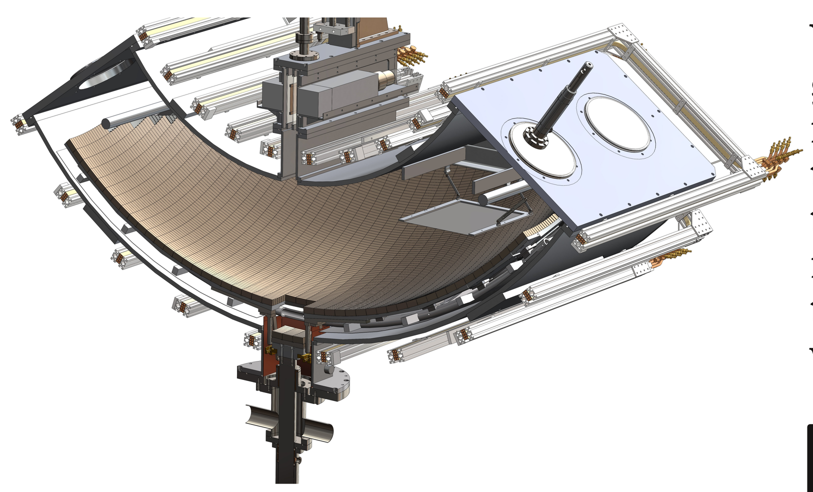


FIG. 3: A cutaway rendering of the trap, including the vacuum chamber. Access to the array is through the end faces of the chamber.

Technical description

- Some initial field mapping has already been done over small sections of the array (Fig. 2), but a solution is needed to map the field in the entire trap without removing it from the vacuum chamber (Fig. 3).
- A system using a gantry holding a Hall probe is one option, but the curved geometry of the trap and the high cost make it less viable.
- An alternative is to track the position of a rover driving around the array while holding a Hall probe close to the surface.

Requirements

A suitable field mapping system should meet the following requirements:

- Have mm-level position resolution
- Measure fields up to 2 T
- Have automated control
- Be able to operate with the trap remaining in the vacuum chamber (though not pumped down)

While a field mapping system using a gantry holding a Hall probe satisfies the first three requirements, being able to map the field without removing the trap from the vacuum chamber and with the holding field coils in place is desirable, as replacing the array and maintaining alignment in the vacuum chamber is very difficult.

Rover

The rover must carry around the Hall probe, several markers needed for optical tracking, a central controller, and various components to support these items. The current prototype is constructed out of aluminum, as the eventual device will likely be.

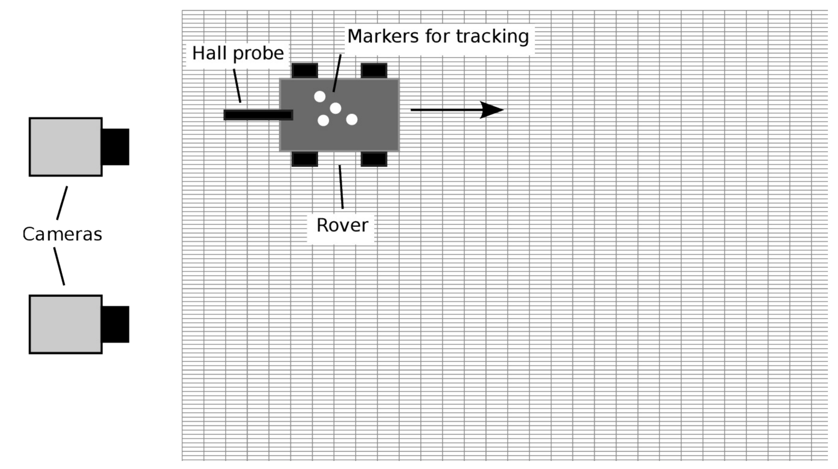
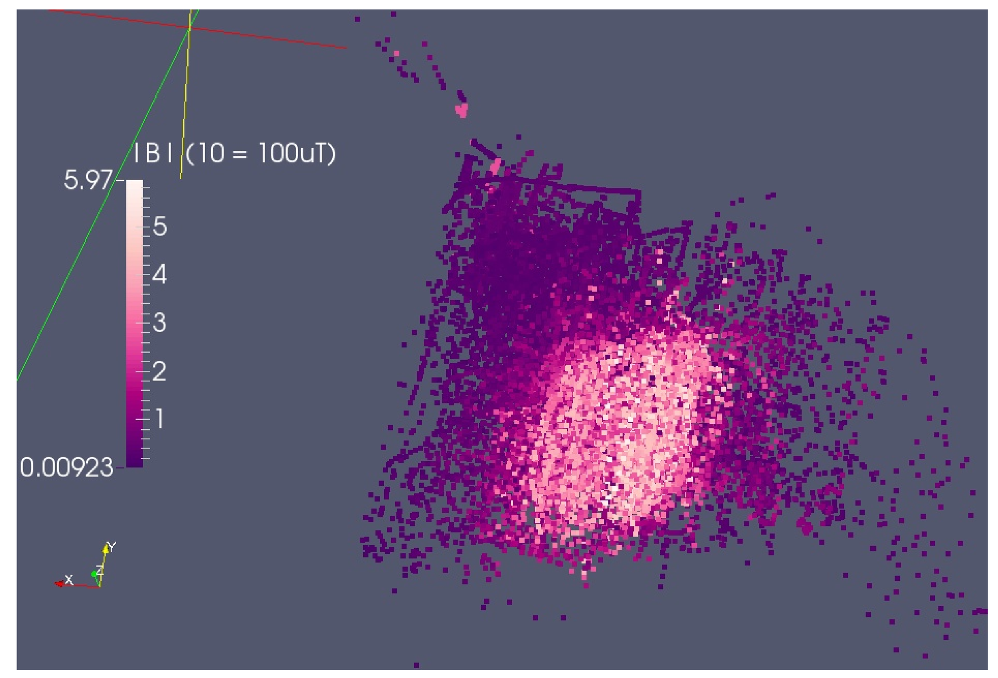


FIG. 4: An illustration of the system operating on the Halbach array.

Results

A demonstration map was created in front of a small coil using a marker attached to a fluxgate magnetometer probe.



This view is from behind the coil looking towards the cameras. The cone shape represents the overlap in the cameras' fields of view.

More work needs to be done to produce more useful maps, primarily implementing a more robust tracking method and studying methods to interpolate this scattered data.

Optical tracking

To create a field map, it is necessary to record all three components of the magnetic field, the translational position of the probe, and the rotational orientation of the probe (i.e. three Euler angles).

An effective method of finding the absolute translational position and rotational orientation of the rover (and thus the Hall probe) is to triangulate the positions of several markers attached to the rover using at least two cameras and computer vision techniques [2]. The OpenCV library [3] has many useful functions for this task.

FIG. 5: A pair of images captured by the stereo cameras at approximately the same time, in front of the coil discussed above. The bright spots are reflective markers attached to the fluxgate magnetometer probe. The data shown above was collected using a single attached marker; these images were recorded to develop another tracking method.

Future work

- Finish constructing rover.
- Investigate other tracking methods.
- Implement simple interface to control rover, construct visualization
- Add an outrigger arm to drag the Hall probe along the surface

There are several components that could be added to the system to improve performance:

- An IMU (Inertial Measurement Unit; a combination of an accelerometer and a gyroscope) to interpolate between optical position measurements and have position measurements available to match the kHz-scale bandwidth of the Hall probe.
- A rotary or linear encoder could be used along with the arm to measure the motion of the Hall probe along the surface and include the surface profile of the trap in maps.

Conclusion

- Design of system, construction of initial prototype is mostly complete.
- While there are still several facets of the design yet to be investigated that could determine the feasibility of the system for its desired use, it seems reasonably possible this system could perform the field mapping satisfactorily.
- The computer vision tracking techniques being used in this project could also be useful in other mapping applications, such as room volume scans.
- For instance, a motion-tracked fluxgate magnetometer could be used to map the residual magnetic field inside a shielded environment for a neutron electric dipole moment experiment under development at LANL.

References

[1] Salvat, D. J., et al. "Storage of ultracold neutrons in the magneto-gravitational trap of the UCN τ experiment." *Physical Review C* 89.5 (2014): 052501.

[2] Farinella, Giovanni Maria, Sebastiano Battiato, and Roberto Cipolla. *Advanced Topics in Computer Vision*. Springer, 2013.

[3] http://opencv.org/

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