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Title: Magnetic field mapping of the UCNTau magneto-gravitational trap: design study

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Magnetic field mapping of the UCNτ magneto-gravitational trap: design study

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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. The UCNτ experiment in development at Los Alamos National Laboratory (LANL) plans to explore better methods of measuring the neutron lifetime using ultracold neutrons (UCNs). In this experiment, UCNs are confined in a magneto-gravitational trap formed by a curved, asymmetric Halbach array placed inside a vacuum vessel and 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 by material interaction can occur at a rate similar to the loss by beta decay. A map of the magnetic field near the surface of the array is necessary to identify any such defects, but the array's curved geometry and placement in a vacuum vessel make conventional field mapping methods difficult. A system consisting of computer vision-based tracking and a rover holding a Hall probe has been designed to map the field near the surface of the array, and construction of an initial prototype has begun at LANL. The design of the system and initial results will be described here.

CONTENTS

I. INTRODUCTION

In many situations, particularly those involving a small volume or simple geometry, constructing a magnetic field map of a volume is a relatively straightforward task: one can often simply attach a field probe to a setup involving three motors and track their motion. This sort of conventional approach is not suitable for mapping the magnetic field near the surface of the Halbach array (seen in Fig. 1) used in the UCNτ experiment, as the trap's enclosure in a vacuum vessel make any form of this conventional field mapping very difficult. This report will focus on the design of an alternative system involving a rover and computer vision tracking at a high level and omit many technical details of the system.

II. BACKGROUND

The UCNτ experiment being developed at LANL seeks to investigate better methods of measuring the beta decay lifetime of the free neutron using ultracold neutrons (UCNs) confined in a several m^3 volume. The experiment is based on the concept presented in reference [1].

A. Ultracold Neutrons

Ultracold neutrons are neutrons that have been cooled down to kinetic energies below approximately 300 neV with several useful experimental properties. The kinetic energy is on the order of both $\boldsymbol{\mu} \cdot \boldsymbol{B}$ with $\boldsymbol{B}$ on the order of 1 T and the gravitational potential energy mgh with h on the order of 1 m. Additionally, they can be stored in containers of certain materials (e.g. stainless steel, nickel, copper, quartz) by total external reflection. These properties allow UCNs to be manipulated with materials, gravity, and easily-attainable magnetic fields. A detailed discussion of the physics of UCNs is available in reference [2].

B. Magneto-gravitational trap

The magneto-gravitational trap used in the experiment, shown in Fig. 1, consists of a Halbach array (an array of permanent magnets or current-carrying coils arranged with rotating magnetization vectors so as to create a strong, exponentially-decaying field on one side and a near-zero one on the other) placed inside a vacuum vessel. The UCNs are confined in the trap from above by gravity and from below by the magnetic field. A high vacuum is necessary to prevent loss of UCNs to interaction with gas molecules.

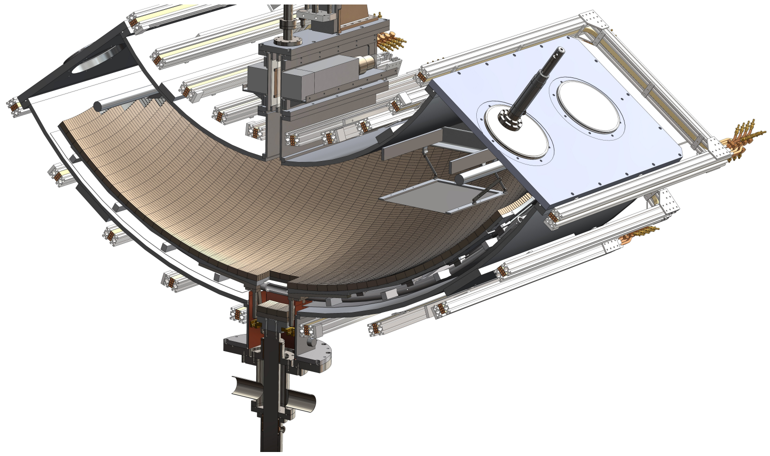

FIG. 1. A cutaway rendering of the vacuum vessel and Halbach array used in the trap.

Some defects such as chips in magnets or relatively large gaps between magnets are present in the Halbach array. If any of these defects are sufficient to reduce the local field below that required to repel the desired energy level UCNs ($|\boldsymbol{B}| \geq 0.8\,\mathrm{T}$), loss due to material interaction will occur, possibly creating a significant systematic shift in the lifetime measurement.

Mapping of the magnetic field over the entire surface is necessary to identify and correct any such defects; only scans over small sections of the assembled array have been performed previously[1]. The curved, asymmetric geometry of the trap and its placement inside a vacuum vessel make conventional methods of field mapping (e.g. a gantry robot) difficult and costly, so an alternative design to map the field with the array remaining in the vacuum vessel is desired.

The design that will be detailed here involves using computer vision techniques to track the position of a rover carrying a Hall probe.

III. SYSTEM OVERVIEW

This design consists of two major components: a rover that travels along the surface of the array and a computer vision system that tracks its position

[1]Each $\sim 6" \times 6"$ subpanel was mapped for quality control before final assembly into the array, but these defects (chips, gaps) were a result of the final assembly process

(and thus that of the Hall probe) in six degrees of freedom (6-DoF, i.e. x, y, z, θ, ϕ, ψ) in order to create field maps. Auxiliary components of the system, such as the data processing and interpolation will also be discussed. A very simple illustration of the system is shown in Fig. 2

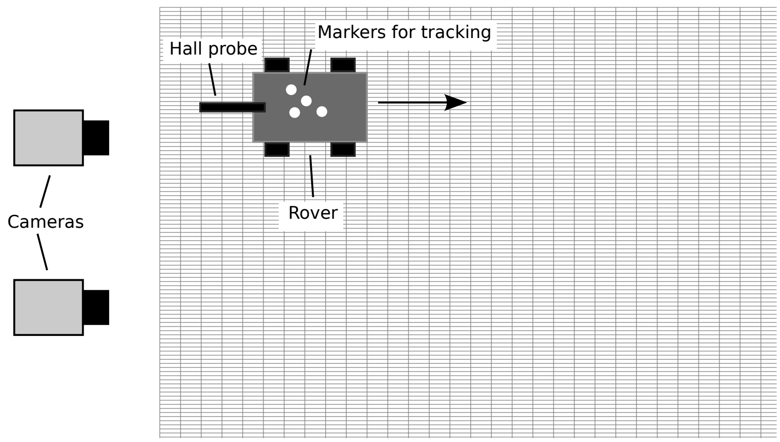

FIG. 2. A rough overview of the operation of the system design described here.

IV. ROVER OPERATION

A. Data acquisition

The Hall probe being used (Senis H3A) is designed to be operated with a supplied transducer that supplies power to the Hall sensor and conditions the output signal. With this arrangement, the transducer produces three differential outputs directly proportional to the strength of each component of the magnetic field, along with a differential signal representing the temperature of the probe for compensation. An analog-to-digital converter (ADC) to acquire data from the transducer must therefore have at least four differential inputs and be able to sample all channels simultaneously at a rate similar to the bandwidth of the transducer. The four-channel ADS1274 and eight-channel ADS1278 from Texas Instruments and the MAX11040K from Maxim Integrated are 24-bit ADCs that satisfy these requirements.

An ADS1278 evaluation board could not be made to work, so a pre-configured USB ADC was used to collect data for an initial demonstration.

While the current system appears adequate for demonstrations, it is not ideal in that it only has 12 bits of precision, and reads the multiplexed channels sequentially. Perhaps the ADS1278 evaluation board was not designed to work standalone using SPI. Creating a PCB to integrate either the MAX11040K or ADS1278 with the appropriate level-shifting circuitry and microcontroller should be straightforward and hopefully work more predictably.

The level shifting from the $\pm 10\,\mathrm{V}$ signal from the Hall probe to below $2.5\,\mathrm{V}$ for the ADS1278 or $2.2\,\mathrm{V}$ for the MAX11040K can easily be accomplished with an op amp configured as a summing amplifier, as described in detail on this website[2].

B. Encoder

An encoder is a device that measures rotational or linear position, either in absolute terms or with an incremental signal that toggles for a given, usually very fine division. A linear or rotary encoder can be used to measure the elevation profile of the surface by measuring the displacement of an arm that allows the Hall probe to follow the surface. One option for an absolute rotary encoder is the ROC-413 [3] from Heidenhain, which has 13 bits of precision, corresponding to an angular resolution of $2\pi/2^{13} = 0.77\,\mathrm{mrad}$.

C. Controller

There are a number of options for a system to control the motion of the rover, acquire data from the Hall probe, and communicate with the primary data acquisition computer. Perhaps the most obvious option is to use a conventional microcontroller, like a PIC or AVR. However, the BeagleBone Black from Texas Instruments is a single-board computer with a number of appealing characteristics. It is essentially a fully-capable ARM computer running Linux (Debian by default) with several low-level interfaces.

It may, however, be more suitable to instead use a conventional microcontroller, as the ADC used for the Hall probe may need a controller that can be more easily be made to respond to interrupts, and issues may arise with the less predictable timing of the computer.

[2] http://masteringelectronicsdesign.com/design-a-bipolar-to-unipolar-converter/

[3] http://www.heidenhain.com/de_EN/php/documentation-information/brochures/popup/media/media/file/view/file-0034/file.pdf#page=50

D. Power

The power source currently being used for the rover is a 12.8V 9.9Ah $LiFePO_4$ battery. While slightly more expensive than other Li-ion or NiMH batteries, $LiFePO_4$ batteries have several advantages, notably including increased safety.

While building DC/DC switching regulators on a control board to supply these voltages would be a very reasonable approach, there are several prebuilt modules available that are very simple to use, and perhaps even more space-efficient because they integrate the required inductor which would otherwise be quite bulky on the board.

E. Control

There exist several potential options for controlling the path of the rover. Perhaps the most robust of these would be to incorporate feedback between the vision tracking system and the controller. The current tracking methods that have been studied should easily be able to provide a calculated position a few times each second, so this control method should be viable with some additional hardware for communication.

Due to the likely short distance between the rover and the camera data acquisition computer and the small amount of data to be transmitted, the easiest way to implement this control scheme would likely to use a pair of ZigBee transceivers to send the magnetic field measurements to the data acquisition system and motion commands to the controller upon completion of the position calculation algorithm. The Atmel TZB-RF-233-1-CR is a ZigBee transceiver with an SPI interface that can be used with the rover controller; the Telegesis ETRX357USB is a transceiver with a USB interface that could be used on the data acquisition system (or, very well on a BeagleBone Black instead of an SPI module).

If this proves difficult, executing a series of commands pre-programmed in the rover controller should be easy and viable for controlling the rover.

F. Mechanical components

The current prototype of the rover (which has yet to be thoroughly tested) consists of an aluminum frame and a pair of brushed DC motors elevated around 5 cm from the bottom of the wheels, which may be sufficiently far from the array surface for the motors to operate correctly; this distance can easily be increased.

V. OPTICAL POSITION TRACKING

In order to build up a field map, all three components of the magnetic field read by the Hall probe must be recorded along with the translational position and the rotational orientation (the Euler angles) of the probe. One effective way to track the mobile rover in 6-DoF is with a computer vision system that uses two (or more) views of an object to find its translational position and rotational orientation.

A single marker attached to the probe is sufficient to find the translational position of the probe, but a cluster of four non-coplanar points are required to find the translational position in three dimensions and the three Euler angles that specify the rotational orientation of the probe. A program to track the probe using a single marker has been completed; a program implementing tracking using a cluster is nearly complete aside from the final transformation calculation.

A. System components

1. Cameras

The central component of the optical tracking system is, of course, the cameras. A pair of Basler acA640-120gm cameras along with 4-12mm f/1.2 lenses are being used in the initial prototype. Machine vision cameras such as the Basler model used here are much more appropriate in this application than devices like webcams, as they offer a number of features including the ability to apply a hardware trigger to synchronize multiple cameras and a good API.

2. Tracking markers

One method of making a point in an image easily distinguishable from the background is to use a retroreflective marker attached to an object in conjunction with infrared-emitting LED lamps placed near the cameras and infrared longpass filters used on the cameras. This setup creates images such as those shown in Fig. 3.

FIG. 3. Image captured from a Basler camera using an IR longpass filter with IR illumination; the bright spots are retroreflective markers attached to a fluxgate magnetometer probe.

B. Marker tracking

The first step in calculating the position of the rover is to find the image coordinates of the attached spherical marker(s) in each view.

Before any algorithm is used to find the circular objects in the images, it is useful to apply a threshold to the image to prevent noise or extraneous objects being mis-identified as markers. This can be performed using the OpenCV function `threshold` with the type `THRESH_BINARY`, which assigns the value of `maxval` (e.g. 255 for white) to all pixels with a values above `thresh` and 0 (black) to all below it.

The image coordinates of a single marker can be calculated by finding the "center of mass" of the bright area in the image using `cv::Moments`. A Hough transform (e.g. as implemented in `cv::HoughCircles`) can find the coordinates of multiple markers in an image.

An implementation of this algorithm is available in OpenCV that makes use of a GPU for processing through nVidia's CUDA framework. Algorithms that are highly parallel can be implemented efficiently using GPUs, and the Hough transform seems to fit this structure. Indeed, several papers note dramatic performance increases using a GPU implementations of the Hough transform circle-finding algorithm.

Only very minor changes are required to use the GPU implementation of `HoughCircles`. The syntax is essentially the same, primarily the data structures used are different.

Once the image coordinates of the markers are found, the coordinates in each view can be used along with certain parameters relating to the orientation and internal distortion of the cameras to find the world coordinates of the markers. In the single-point case, this information is sufficient to build a field magnitude map, and a vector field map if the probe can be assumed to have been held in the same orientation.

In the multiple-point case, the transformation between some origin position of the cluster and the measurement point must be estimated. This transformation can be described using a 4×4 matrix, and suitable functions are available in the Point Cloud Library[4]; e.g. `pcl::registration::TransformationEstimation`. The multiple point case will be somewhat more difficult to implement, due to the need to track markers between views and frames, among other factors, but this approach will be necessary to measure the position and orientation of the probe on the curved surface.

1. IMU

One appealing complement to the stereo tracking system is the use of measurements from an Inertial measurement unit (IMU). IMUs generally consist of a 3-axis microelectromechanical systems (MEMS) accelerometer and 3-axis MEMS gyroscope in one package. IMUs have the advantage of rapid update rates and precise measurements on small timescales, but the double integration of the accelerometer data to find position can result in issues with drift as noise accumulates. Stereo vision tracking systems, on the other hand, have good absolute accuracy but the Basler cameras mentioned before are limited to a 120 Hz acquisition rate—far from the $\approx$5 kHz bandwidth of the Hall probe. There are several suitable models, such as the MPU-6050 pictured in Fig. 4.

[4] `http://pointclouds.org/`

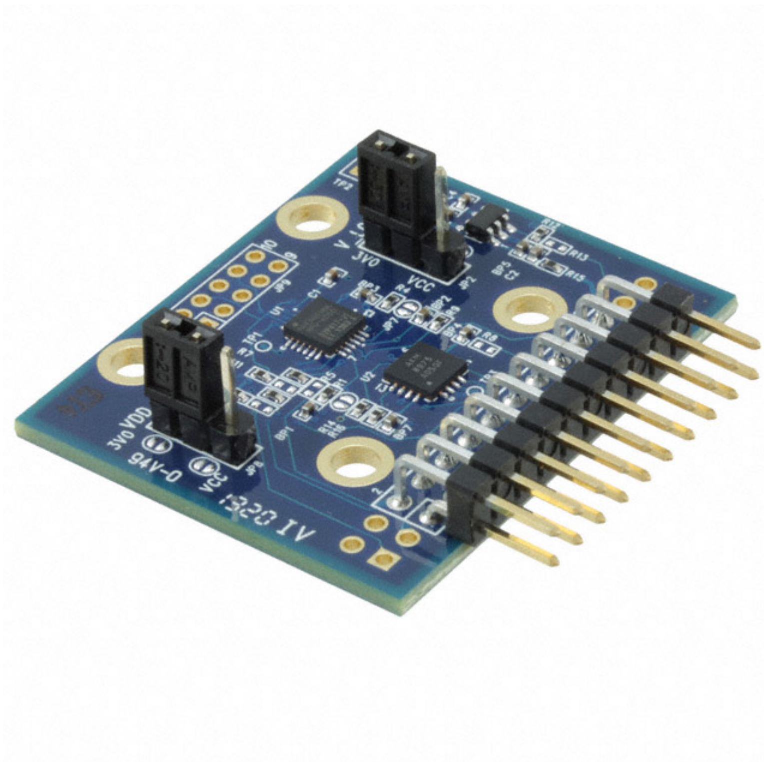

FIG. 4. The evaluation board of the MPU-6050 produced by InvenSense, an IMU that could be used in the system. Source: digikey.com

C. Visualization

Simply plotting the magnetic field measurements in three dimensions with color corresponding to the magnitude at each point produces the result in Fig. 5. Some sort of interpolation is necessary for a more useful map of the data. Basic grid interpolation will not work due to the scattered nature of the data; instead we can use radial basis function interpolation, which assigns a value to any point by weighting the values neighboring points according to some (e.g. Gaussian) function.

D. Results

So far, a map (shown in Fig. 5) of the field surrounding a solenoid of radius $\approx$10 cm has been created to investigate the viability of the current system.

This position data was collected by triangulating the position of a single marker attached to a fluxgate magnetometer probe. The envelope of the data represents the overlap of the two cameras' fields of view.

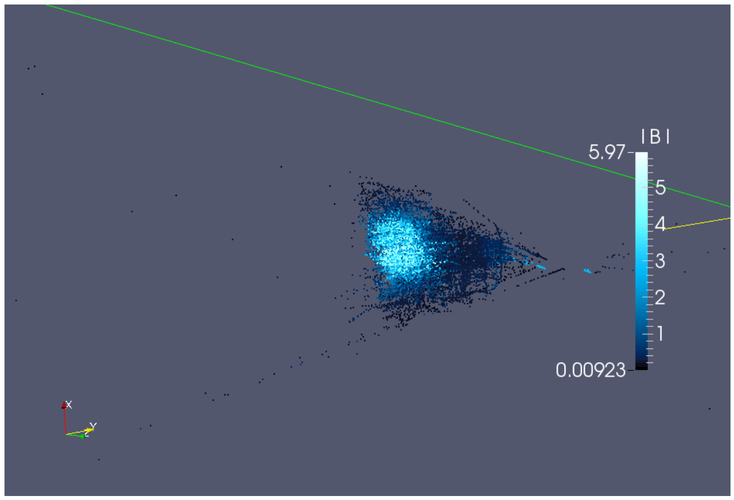

FIG. 5. Map of the field near a solenoid displaying discrete point samples. The scale represents a voltage measurement on the scale 100μT/10V.

E. Other applications of technique

The versatility of the optical tracking scheme compared to a field mapping system tracking the motion of a probe along a fixed path or in a small volume allows for several potentially useful applications of this technique, such as performing room volume scans to locate problematic magnetic field gradients for a neutron EDM experiment, and to assess the effects of degaussing mu-metal panels on the $\boldsymbol{B}$-field inside a magnetically shielded environment. This technique should also be useful for many similar field mapping applications where the cameras have a line-of-sight to the area of interest and a probe can be moved through the volume (e.g. by hand).

VI. STATUS OF PROJECT

So far, the computer vision system has been shown to work at least at a basic level, but other tracking methods that are able to track the rotation of the probe need to be implemented. Additionally, other methods of interpolation of the magnetic field data need to be studied. The overall design of the rest of the system has largely been completed, and most of the other components have been selected.

The alternative possibilities for performing this field mapping, such as a large gantry system, would require not only the removal and replacement of the large and heavy array, but also a delicate realignment during the replacement. In comparison, the design presented here will be able to perform this mapping without removing the array from the vacuum vessel, and seems feasible to implement. While the primary motivation for this design is the ability to create maps without removing the array from the vacuum vessel, the cost of this system should be substantially lower than that of the gantry system.

VII. FUTURE WORK

Listed below are some tasks related to the tracking system that need to be completed:

- Determine spatial precision and accuracy of optical tracking system
- Implement 6-DoF tracking using a cluster of points attached to the probe or more robust markers such as a reflective grid on the probe
- Investigate interpolation methods for field data, perhaps taking advantage of known properties of magnetic fields (e.g. $\nabla \cdot \boldsymbol{B} = 0$)
- Implement a 24-bit simultaneous-sampling ADC

Listed below are some tasks specific to the rover system that need to be completed:

- Finish constructing rover chassis
- Select, program controller
- Implement wireless communication with image processing system
- Investigate actual power consumption of finished system; switch to smaller battery if possible
- Investigate mounting system for Hall probe, including encoder

VIII. CONCLUSION

With the technical and design work that has been done so far, it seems reasonably possible that this sort of rover-based system would be able to create maps of the magnetic field in the UCNτ Halbach array, though much work still needs to be done. The viability of the optical tracking scheme as demonstrated so far is seemingly appropriate for use in other mapping applications, although some improvements could be made especially with regards to the ADC and orientation tracking.

IX. ACKNOWLEDGMENTS

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