**Real-Time, Non-Contacting Position Tracking of Medical Devices and Surgical Tools through the Analysis of Magnetic Field Vectors**

Mohammad Odeh1

Edward Daniel Nichols1

Fluvio Lobo1

Jack Stubbs1

Institute for Simulation and Training, Center for Applied Research, University of Central Florida1

# 1 Background

As the demand for increasingly advanced invasive medical procedures rises with the average age of the population, it also becomes increasingly compelling to facilitate and extend the spatial awareness and dexterity of surgeons, both human and robotic. One may accomplish this by tracking an object digitally and representing its form and motion in a close virtual model of the area around an incision, such as through an augmented reality platform. Several groups across a diverse range of academia and industry have competed to develop marginal improvements to methods of digitally tracking objects [1, 3, 5, and 6]. In the entertainment industry in particular, object tracking is a fundamental way of bringing life-like motion to an object represented in virtual space. The generally accepted approach is to use expansive, multi-camera computer vision (CV) systems to yield real-time tracking [4]. However, this approach is not suited for medical applications; CV is limited by a strict field of view. Accurately tracking surgical instruments inside of organic tissues must then be done another way.

Of the methods presently being investigated, none are as applicable in a medical context as magnetic field sensing. Human tissues are permeable to magnetic flux, and magnetic fields are well characterized. Upon this motivation, we have constructed an inexpensive device from off-the-shelf parts that enables the tracking of a permanent magnet on surfaceto serve as a foundation for future work in this field.

# 2 Methods

## 2.1 Analytical Foundation

Electromagnetic fields are characterized by fundamental principles. Given a classic magnetic dipole centered at the origin, its magnetic induction can be expressed as:

|  |  |
| --- | --- |
|  | (1) |

Whereby the relationship is dependent on the orientation and strength of its magnetic moment vector, given by, as well as the location of the arbitrary point of interest with respect to the center of the magnet, represented by vector. Equation (1) can be modified to express the strength of the magnetic field **,** which is what an observing magnetometer normal to the level surface of the magnetic field would perceive; which may further be broken into a more convenient polar component form, given the intrinsic rotational symmetry of isofield lines about .

Based on the work of Chen *et al* [5], expressing the location of the center of a magnet with respect to the magnetic field vectors observed by three sensors in predefined relative positions fully satisfies a system of equations when the magnet is in a fixed North pole orientation along the system’s internally defined z-axis:

|  |  |
| --- | --- |
|  | (2) |
|  | (3) |
|  | (4) |

Whereby, represents a sensor in the array, is the distance to the center of the magnet for the sensor, is the relative offset from a designated origin with respect to the sensor, represents the angle made by the north pole of the magnet and the radial component of, and K represents a constant that encompasses the magnitude of the dipole moment, magnetic permeability of free space, and the relative permeability of the magnet’s own material.

However, one must maintain certain minimum assumptions for a solution to converge numerically.

1. An origin must be defined with respect to the relative fixed positions and orientations of the sensors.
2. The constant value of the magnetic field strength coefficient K of an arbitrary magnet has been closely approximated, or is otherwise known.
3. A constant magnetic field source of perceivable threshold exists within range of at least three sensors in the sensor array.

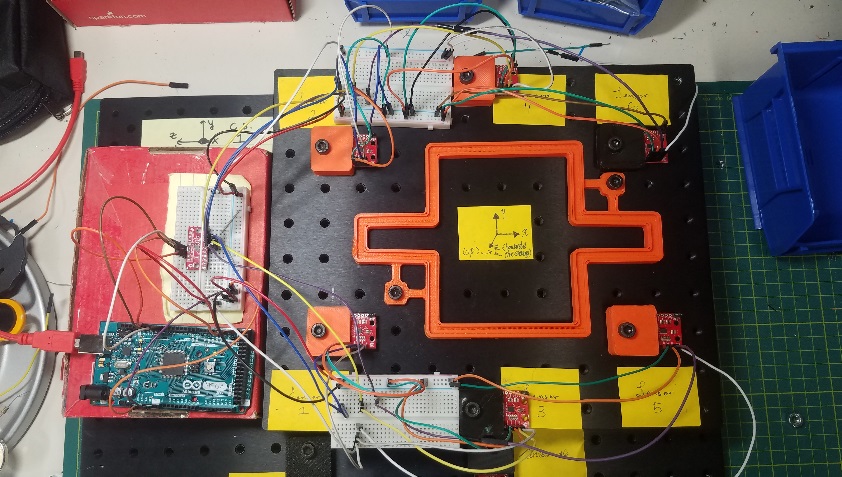
In addition, to refine accuracy, certain physical restrictions facilitate these conditions.

1. Ambient magnetic fields must be mitigated; or the signal must be otherwise overcome.
2. The magnet’s form factor is minimized to yield closer adherence to presupposed principles.

To begin achieving these conditions, we designated the sensor in the bottom left corner of our 2D sensor array (Figure 1) to be the origin. All sensors’ axis in the array are aligned with each other.

## 2.2 Magnet Selection and

While the work of Chen *et al.* [6] has demonstrated feasibility of multiple object tracking using electromagnets, our team decided to pursue an approach that would require the least number of modifications to the device, tool or end-effector to be tracked. Hence, two permanent magnets were chosen as the target. Furthermore, both magnets were assumed to have an ideal magnetic dipole field. The magnitude of each magnet’s dipole moment K was calculated empirically (Table 1).



*Figure 1: Sensor Array with a 3D printed magnet test track inside.*

## 2.3 Empirical Approximation of K

Instead of theoretically approximating the value of K [], our team devised an empirical approach using a single *SparkFun LSM9DS1 IMU* and a custom CNC machine. Three out of the nine degrees of freedom (DoF) from the *LSM9DS1 IMU* are given by a magnetometer, used here measure the strength of the magnetic fieldgenerated by the permanent magnet in question. The CNC was then used to move the permanent magnet precisely, along a single axis ( axis), towards the magnetometer, thus simplifying Eqns. (2), (3) and (4) into Equation (5).

|  |  |  |
| --- | --- | --- |
|  |  | (5) |

The actual protocol for the approximation of K, for each magnet, can be summarized in the following six steps:

1. The magnet was placed at a distance of 75mm away from sensor *i* such that (,) and (,).
2. A sample of K was computed from for sensor *i*.
3. The magnet was moved =10mm to (,).
4. Another sample of K was computed from a new.
5. Steps 3 and 4 were repeated multiple times, recording the values of x, and K each time.
6. An approximated result of K yielded from averaging the sampled points.

Readings of and should be minimized to ensure accuracy; and condition is satisfied when and. As long as both the approximated value of K yielded physically reasonable position solutions. Nonetheless, the closer and were to zero the better the approximation.

## 2.4 2D Sensor Array

Having calculated K, our team proceeded to build a set-up capable of tracking either magnet. While only three magnetometers were required to derive the position of the magnets, an array of six *SparkFun LSM9DS1 IMU* was built to enclose a tracking area and extend the tracking capabilities of the system. Due to I2C address conflicts, magnetometer communication was mediated using a *SparkFun 74HC4051 8-channel* *multiplexer*. Data was driven through an Arduino-compatible microcontroller such as the *Arduino Mega 2560* or *PJRC’s Teensy 3.2* (Figure 1). Microcontrollers formatted and transmitted magnetometer data through a Serial Bus to a PC running a custom Python script.

Sensor readings were taken by the magnetometers at 80Hz, yielding the XYZ components of with respect to the sensor orientation. Geomagnetism was partially accounted for using the board’s built-in declination adjustment function. To mitigate the effect of remaining ambient magnetic fields, sensor readings were averaged over 50 readings, for each sensor, upon reset and the respective result was subtracted from later readings. Drifting was observed to be minimal, yet further mitigation was left as future work. Readings henceforth started at ±20 Milligauss and ranged to ±16 Gauss, according to the built-in 16-bit analog to digital converter in the chip.

## 2.3 Position Tracking Algorithm

Data retrieval and position tracking was driven by a custom Python script developed on a PC. Based on Eqns. (2), (3) and (4), each magnetometer allowed the Python script to assemble one equation, for a total of six equations using the entire array. The resulting non-linear system had no analytical solution, thus requiring a numerical approach. SciPy’s implementation of the Levenberg-Marquardt (LMA) method was used to solve the resulting non-linear system. Given that SciPy’s LMA lacked support for over-constrained systems, three of the six magnetometer were ignored on every iteration. The script constructed the system of equations using the data from the three magnetometers with the largest.

The LMA was chosen for its robustness and speed of convergence. SciPy’s LMA combines Newton-Raphson’s algorithm and the Steepest Descent method to converge even in the case of a poor initial guess. However, like any numerical method, effective convergence still relies on the initial guess’ proximity to the solution. To overcome this issue, the centroid of the triangle described by the three magnetometers with the largest readings was used as the initial guess.

Upon convergence of the LMA, values were logged to determine point accuracy (Table #, #) and motion tracking capabilities (Figure #-#). The entire process described above, from sensor calibration to data collection and numerical solution has been summarized in Figure #.

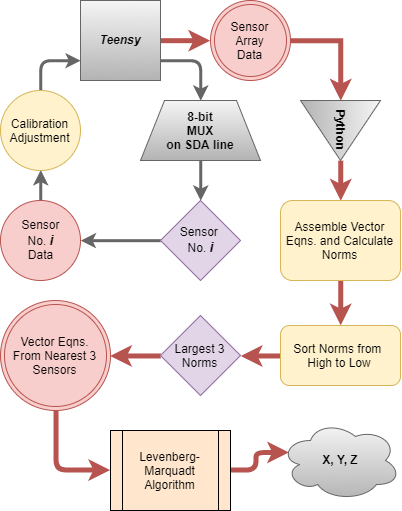


Figure 2: System Flowchart

# 3 Results

Given the demonstrated success of others operating under a similar approach [2, 6 and 7], our focus becomes refining the system for operational efficiency. ***However, we conducted a series of trials to verify and characterize the system’s accuracy and precision, especially in pursuit of our lab’s application, in 2D space.***

## 3.1 Point Accuracy

Using a metric optics breadboard with 25mm separation between through-hole taps, a 30mm diameter permanent magnet, and 3D printed magnet jigs, output was sampled at convenient, known points on a plane level with the sensors. Several hundred output samples were taken for each point.

|  |  |
| --- | --- |
| *Distance Error from (100mm, 100mm, 0mm)* | |
| **Mean** | **3.774** |
| Standard Deviation | 0.510 |
| Sample Variance | 0.260 |
| Kurtosis | 0.749 |
| Skewness | -0.140 |
| Range | 4.064 |
| Minimum | 1.614 |
| Maximum | 5.678 |
| Count | 576 |

Figure 3: Example of descriptive statistics for the data sampled from the system with the center of the 30mm diameter magnet mounted on a jig at the point  
 (100mm, 100mm, 0mm).

After 20 points were sampled, a mean “distance error” was calculated for each point. We take then a mean of means to return a more complete reported precision of within 1.5mm for a 30mm magnet with an approximated value of K.

|  |  |
| --- | --- |
| *System Distance Error (mm)* | |
|  |  |
| **Mean of Means** | **1.402** |
| Standard Deviation | 0.774 |
| Sample Variance | 0.599 |
| Kurtosis | 3.802 |
| Skewness | 1.642 |
| Range | 3.325 |
| Minimum | 0.449 |
| Maximum | 3.774 |
| Count | 20 |

Figure 4: Reported System Error from 20 samples.

## 3.1 Motion Tracking

Furthermore, we designed and 3D printed a few arbitrary tracks to place on our breadboard…

**[FLUVIO CONTINUES HERE]**

**[MENTION TRIAL TIMES AS COROLLARY TO THROUGHPUT RATE]**

**[ALSO, IT MAY ALREADY BE TOO LONG; WE’LL HAVE TO TALK ABOUT CONDENSING THE PAPER]**

The results are;

1. ~~Sensor array for real-time, non-contacting tracking of an object along a plane~~
2. An robust algorithm for the real-time, no-contacting tracking of an object in space (3)

The robustness of our sensor arrays (devices) and analysis software was evaluated in terms of;

* Examples of data plot
* Speed of the data
* ~~Accuracy and precision~~

# 4 Interpretation and Future Work

***We encounter many limitations in the present form of the system, indirectly related to the demonstrated principle, such as sensor readings’ drift affecting the distance error, limited software stability driving throughput inefficiency, a lack of a virtual 3D visualization of the output for ease of use, etc.*** Hence, further optimization is required, especially and including, a more robust mitigation of ambient fields and the throughput rate (which is heavily dependent on computation time). Finally, a thorough characterization of the system’s performance in 3D space, especially at random orientations of the magnet, must still be done.

Moving forward beyond these present preoccupations, with our medical applications in mind, we intend to improve upon the system, by optimizing the execution of LMA with better initial guesses and smoother data inputs; enable the approximation of a magnet’s orientation, by tracking the path of the magnet and the sensor array’s magnetic field vector components across time; increase the measurement accuracy, by refining approximations of K; miniaturizing the device to a more convenient form; and moving to more complex multi-pole objects, such as combinations of magnets; and building a 3D visualization of system output in real-time.

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