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

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# Background

There has been remarkable growth in the adoption of robotically assisted surgeries, especially as their benefits to productivity have become apparent. For example, dramatic reductions in patient recovery times have been observable as systems like Intuitive Surgical’s *Da Vinci* have become increasingly integrated as cornerstones of minimally invasive procedures. To highlight just how quickly this technology has gained prevalence, Beasley writes the *Da Vinci* “was used in 80% of radical prostatectomies performed in the U.S. for 2008, just nine years after the system went on the market” [8].

The *Da Vinci* is not alone. Competition in the field is increasing, driving the development of more versatile, more cost-effective and more autonomous systems. However, robotic systems carry the inherent technical requirement for accurate, on-demand spatial information about their environments. For example, Renishaw’s *neuromate* and Accuray’s *CyberKnife* both require the precise location of fiducial markers **[REFS]**. [Others, like Cambridge Medical Robotics’ Versius and Medrobotics’ *Flex* operators rely upon active imaging or access to direct line of sight **[REFS]** ].

Hence, as such systems continue to technically advance across a broad scope, that inherent technical requirement for spatial awareness data will only increase. Machine-learning algorithms driving the interconnected array of robotic surgical assistants envisioned by Verb Surgical would need data for processing **[REFS]**; surgeons performing teleoperations across oceans would benefit from the availability of high-quality, real-time, auxiliary sensor information that enables extension of their dexterity and spatial awareness beyond what might be provided for by a robotic platform alone. Furthermore, especially as such technologies proliferate, providers would desire easily deployable, low-profile, cost-effective user input systems for simulation programs designed to train aspiring and established healthcare professionals on using state-of-the-art medical tools.

To advance this field and to fulfill an imperative to provide simulation inputs for our own training applications, we have set out to construct a robust, scalable, highly-customizable, and non-intrusive sensor array system for dynamically tracking point objects in a volumetric space. Given that human tissues are permeable to magnetic flux, magnetic fields are well-characterized, and there exists a wide variety of open-sourced hardware, our system achieves this by precisely and dynamically locating an arbitrary magnetic field source, such as any permanent magnet, in a volumetric space within the range of our array. Ultimately, this extremely low-cost proof-of-concept prototype serves as a foundation for exploring this approach in the medical industry.

# Methods

**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:

|  |  |
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|  | (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 x-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 conditions 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 the optimal 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 their noise 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 sensor array (Figure 1) to be the origin. All sensors’ axis in the array are aligned with each other.

**Magnet Selection**

In accordance with our design prerogative, permanent magnets were chosen to enable a simple but versatile system that can deliver precision without compromising costs. Permanent magnets are readily available in different shapes, sizes and strength. Therefore, surgical tools or medical devices can be equipped with an appropriate magnet that demands only minimal design changes, if any at all. Permanent magnets also do not require power, which further reduces the need for the redesign and adaptation of the tool or device to be tracked.

A disc-shaped, **[VALUE]**mm in diameter permanent magnet was found to comply with our simulation application’s low-modification parameter, so it was chosen to test and evaluate our proof-of-concept system. The magnet’s dipole field was assumed to be ideal and its diploe moment was calculated empirically.

**Empirical Approximation of K for Arbitrary Magnet**

Our team devised an empirical approach to approximate the value of K using a single *SparkFun LSM9DS1 IMU* and a custom CNC machine. The CNC was used to move a fitted permanent magnet precisely along the axis, thus simplifying Eqns. (2), (3) and (4) into Equation (5).

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

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

1. The magnet was placed at 50mm away from the IMU sensor such that it reads.
2. A sample value for was obtained andan accurate approximation for K was computed using Eqn. (5).
3. The magnet was moved by mm to  
   ().
4. Another sample of K was approximated from a new sample of.
5. Steps 3 and 4 were repeated up to =75mm, recording the values of , and K each time.
6. An approximated result of K was yielded from averaging the sampled points.

It was observed that the calculated value of K varies along the different positions. The rigorous characterization of these variations and their impact on the system was left as future work. However, it was also found to be possible to continuously improve the accuracy of the approximated value of K for a magnet by minimizing the and components of the magnetic field readings driven by the magnet during the procedure.

While , the approximated K yielded physically reasonable position solutions. Nevertheless, the marginal gain in accuracy using a more rigorous method was not significantly beneficial to our purpose and the team opted to use the protocol defined earlier to approximate the value of K for any future work.

**Sensor Array and Tracking Algorithm**

***Summarily describe the sensor array and provide a figure of it here.*** *Put body of the paper here. Put body of the paper here.*

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. The script constructed a determinable system of equations using the data from the three magnetometers observing the largest.

LMA was chosen for its robustness and speed of convergence. Solutions typically converge within **[2ms]**. 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 2, 3) and motion tracking capabilities (Figure 3, 4). The entire process described above, from sensor calibration to data collection and numerical solution has been summarized in Figure 2.*

# Results

**Approximation of K**

Following the CNC-based approximation protocol described earlier, the magnitude of the magnetic field moment for the 30 mm permanent magnet was found to be.

**Point Accuracy**

Using an aluminum optical breadboard (600 mm x 600 mm, M6 taps, 25 mm apart) and 3D printed standoffs

Using our 2D sensor array, position tracking accuracy was studied by placing each permanent magnet in 20 different locations within the array. On average, 20 seconds of sensor readings were recorded for each location. The difference between the expected and observed X and Y positions was recorded, in millimeters, as Xoff and Yoff. A percentage error was calculated as the ratio of these differences to the original X and Y positions. The values reported here represent the average position difference and error among the 20 points sampled using each magnet (Table 2, 3).

The position difference and thus the error was observed to be greater in the case of the small permanent magnet. The weaker magnetic field and magnetic field moment K can support this observation.

**Motion Tracking**

In addition to single point accuracy, our system was tested for motion tracking. A 3D-printed track was designed to guide the permanent magnet on a constrained path as its position was approximated by the sensor array. Position in 3D space (x, y, and z coordinates of the magnet) were time-stamp and recorded by the sensor array. Scatter plot were generated for each run (Figure #).

Motion tracking experiments revealed areas of future work for our team. Scatters revealed some position inaccuracies that could be accounted for by considering the motion was not smooth (the magnet was moved along the track by hand). Furthermore, some inaccuracies could also be irrelevant when considering the actual size of the permanent magnet. Two dashed lines, following the color pattern used for the scatter, represent the approximate size of each magnet (Figure 3, 4). Overall position inaccuracies can be inferred by looking at the corresponding track designs (depicted on the top-right corner of each graph). Additionally, each track required a few minutes for completion (data gathering and plotting) which will lead our team to study hardware and software bottlenecks in pursuit of more rapid tracking.

Note that the coordinate system defined by mathematical principles is executed within our LMA algorithm; wherein a cylindrical magnet, orienting its North Pole along the LMA’s X-axis, lays normal to the surface. Yet, our printed output reflects a more convenient representation of the Euclidean space, whereby the LMA coordinate system is rotated about the Y-axis by 90° to yield the common orientation (whereby the X’-axis extends to the right, as in Figure 3 and 4).

INterpretation

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Thanks mom and dad.

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