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Design of A Three-Dimensional, High Speed Magnetic Tracking System with A Permanent Magnetic Source

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ABSTRACT: This paper will present a novel method of using a magnetic tracking system with a purely DC source to locate the position and orientation of a high speed permanent, rare earth magnet in three-dimensional space. The test platform to be designed to be approximately 9-by-15 feet, as opposed to small scale (inches) of other systems. This tracking system will be tuned to locate specified magnetic objects traveling nearly 100 mph. The tracking system uses a bed of sensitive magnetometers to determine not only the strength of the magnetic source, but also the ambient magnetic noise of the environment and its orientation, allowing the system to track in environmentally noisy conditions. The simulations show the feasibility of such a magnetic tracking system for both location and orientation.

I. INTRODUCTION

Magnetic theory, and its principles and practices, have been well studied. Because of this, many modern technical embodiments already exist — including medical applications, wireless identifications, thermal processes, and audio and video processing [1-5]. Additionally, magnetic theory can also be used for object location and tracking. This paper will present a novel technique to track the position and orientation of a high speed magnetic source in three-dimensional space with a detectable range exceeding three feet. Additionally, this system will operate in the presence of environmental magnetic noise. The paper will focus on a permanent magnetic (DC) source, but the same principles could be used for a variety of magnetic source signatures.

II. BACKGROUND

Magnetic tracking itself is neither a new nor a novel idea. This process, in its simplest form, uses an identifiable magnetic signature in a region with a different (or even no) magnetic field distribution. Dozens of applications of these systems are already in existence, but are limited either by accuracy, cost, size, or speed. These active systems are comprised of both AC and DC magnetic fields. Generally, AC systems have high resolution and accuracy. However, these systems also tend to perform very poorly in the presence of ferromagnetic materials such as carbon steel and iron alloys [6]. It is for this reason that DC systems were initially explored [7]. After further investigations, it has been suggested that pure DC systems are not a feasible solution. This is mainly due to the fact that there is no way to account for the presence of the Earth's magnetic field [7]. This is because both the source and Earth's magnetic field would be additive, and inseparable. The traditional solution to this problem is through the use of pulsed DC magnetic sources. This method allows for the near-DC source to be turned on and off, allowing for the source to be measured when active, and the environment to be measured when inactive. Pulsed DC technology has the benefit of producing negligible eddy currents, unlike its AC counterpart, while in close proximity to ferromagnetic materials. This allows for better overall accuracy. However, the pulsed nature of the system is one of its biggest limitations because the system will only be used for tracking a fraction of the time.

III. PREVIOUS SYSTEMS

Several AC and DC tracking system were researched before the current DC system was proposed. [8-12] Information was gathered about the type of sensor and source used, as well as the maximum detectable distance. This information helped define a set of system specifications which are presented in Table 1.

Table 1 - Comparison of Tracking Systems

System	Sensor	Source	Range
1	Hall Effect	Coil Winding	25 mm
2	Magnetoresistive	Magnetic Dipole	100 cm
3	Hall Effect	Perm. Magnet	14 cm
4	Hall Effect	Perm. Magnet	30 cm

Of the tracking systems examines, all either used a Hall Effect (DC systems) or Magnetoresistive (AC system) magnetic sensor. Two systems utilized custom sources and two utilized permanent magnets as sources. The maximum detected distance ranged from 14 to 100 cm with the majority between 14 to 30 cm.

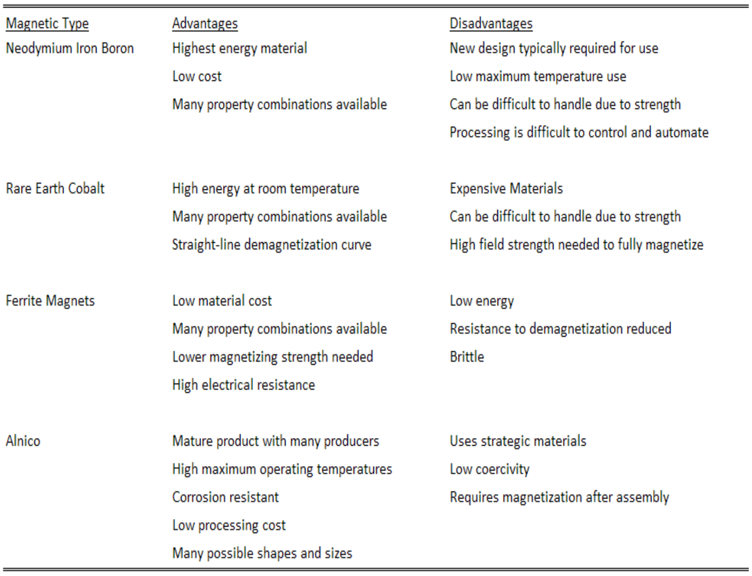
PROPOSED SYSTEM DESIGN

In order for a final set of system specifications to be defined, a sensor type, source type, and maximum detectable range must be defined. The following sections outline how these decisions were made.

4.1 Magnetic Source

Possible magnetic sources for tracking systems can be groups into two categories, active and passive sources. [13] Active sources have an internal power source, and thus are able to emit their own energy, or modulated signature. Passive sources, such as permanent magnets, have no means of producing amplified or otherwise modulated signals. By this definition, naturally occurring active sources are extremely hard, if not impossible to find in nature — and these source must be created and tuned by man. This process adds a level of complexity not needed in passive sources.

A permanent magnet would be one of the simplest magnetic sources. Petrie [14] has identified significant advantages and disadvantages with some of today's most common permanent magnetic sources. A summary can be seen in Figure 1.



Magnetic Type	Advantages	Disadvantages
Neodymium Iron Boron	Highest energy material Low cost Many property combinations available	New design typically required for use Low maximum temperature use Can be difficult to handle due to strength Processing is difficult to control and automate
Rare Earth Cobalt	High energy at room temperature Many property combinations available Straight-line demagnetization curve	Expensive Materials Can be difficult to handle due to strength High field strength needed to fully magnetize
Ferrite Magnets	Low material cost Many property combinations available Lower magnetizing strength needed High electrical resistance	Low energy Resistance to demagnetization reduced Brittle
Alnico	Mature product with many producers High maximum operating temperatures Corrosion resistant Low processing cost Many possible shapes and sizes	Uses strategic materials Low coercivity Requires magnetization after assembly

Figure 1 - Comparison of ferromagnetic materials

Due to the manufacturing and processing techniques, neodymium magnets have only become available for such tracking applications in the last decade. These magnets are an optimal choice for this application because of their high energy potential and low cost. High energy potential yields a higher remanent magnetism, which in turn will yield a bigger magnetic field and a larger detectable distance. Neodymium magnets are available in a plethora of shapes, sizes, and strengths. An optimal configuration needs to be identified for use in tracking applications. Models and equations for disc magnetic and solenoids have been well studied and for a simplistic, practical design, a disc magnet will be used. The generally accepted equation for a solenoid

$$B(x) = \frac{B_r}{2}\left[\frac{x+\frac{l}{2}}{\sqrt{\left(x+\frac{l}{2}\right)^2 + a^2}} - \frac{x-\frac{l}{2}}{\sqrt{\left(x-\frac{l}{2}\right)^2 + a^2}}\right], \qquad (1)$$

where B is the magnetic flux density, B_r is the remanent magnetization, l is the thickness of the magnetic disc, a is the radius, and x is the distance (on-axis) away from the disc, which can be used to define optimal dimensions for the disc. Inspection of the solenoid equation shows that as the diameter to thickness ratio increases, the strength of the magnetic field decreases. Simulations needed to be performed to discover the optimal dimensions for a permanent magnetic source for this system. Optimal dimensions can be discovered by examining the diameter-to-thickness ratio of the permanent magnetic as seen in Figures 2-3. The following analysis was performed with on-axis distances at 0.1 and 1.0 m with *Br* = 100.

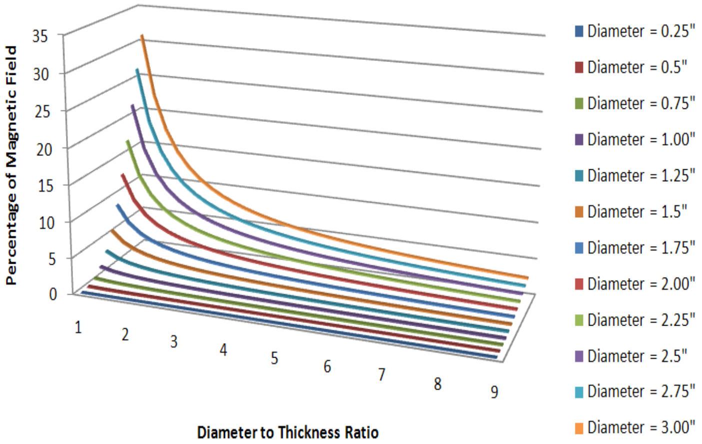


Figure 2 - Graph of the effect of a permanent magnet's diameter-to-thickness ratio on its magnetic field at a distance of 0.1 m for a magnetic disk of various diameters

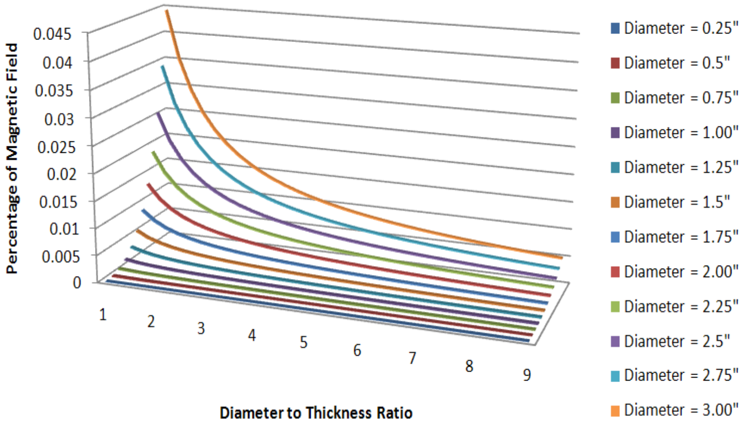
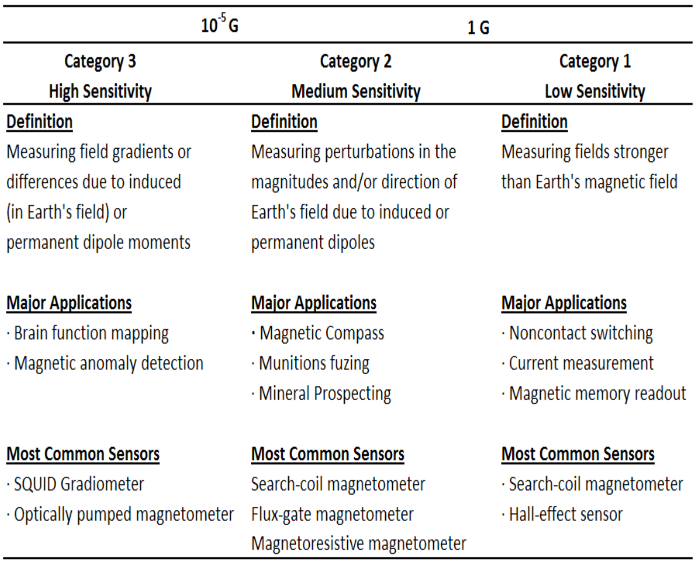


Figure 3 - Graph of the effect of a permanent magnet's diameter-to-thickness ratio on its magnetic field at a distance of 1.0 m for a magnetic disk of various diameters

Based on the figures above, a diameter-to-thickness ratio can be observed, which seems to be dependent upon distance. If x is within 0.001 m (1 mm), then there is no performance difference between diameters or diameter-to-thickness ratios. All points of the field distribution look identical (infinite magnetic source). As the x increases, more prominent diameters and diameter-to-thickness ratios begin to emerge. When x is 0.1 m, it becomes apparent that the best choice for a permanent magnet with diameter to thickness ratio of 1:1 and where the diameter is as large as possible. Again, the best choice is the physical characteristics (i.e. length and thickness) that yield the largest magnetic field strength. This analysis was performed with on-axis measurements, and will also need to be validated for off-axis measurements. For experimental testing purposes, a 13.2 kG neodymium magnet with diameter of 1 inch and thickness of ¼ inch was obtained.

4.2Magnetic Sensor

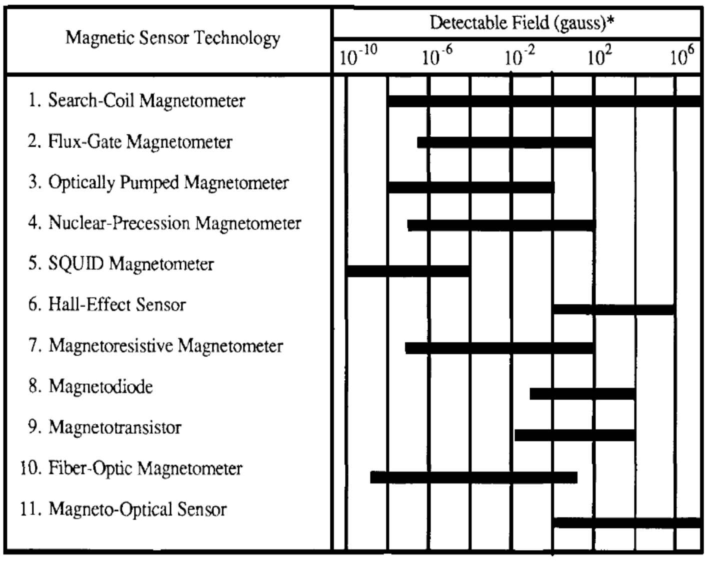
There are a multitude of magnetic sensing technologies available for tracking applications. Lenz [15] defines three categories of magnetic sensing based solely upon their relationship to the Earth's magnetic field strength. The boundary between the first and second categories is defined by the magnitude of the Earth's magnetic field (approximately 0.1 to 1 Gauss). The boundary between the second and third categories is defined by the level at which the Earth's field is stable (below steady state value, approximately 10^{-3} to 10^{-6} Gauss). These categories are show in Figure 4.



10^{-5} G		1 G
Category 3 **High Sensitivity**	**Category 2** **Medium Sensitivity**	**Category 1** **Low Sensitivity**
Definition Measuring field gradients or differences due to induced (in Earth's field) or permanent dipole moments	**Definition** Measuring perturbations in the magnitudes and/or direction of Earth's field due to induced or permanent dipoles	**Definition** Measuring fields stronger than Earth's magnetic field
Major Applications · Brain function mapping · Magnetic anomaly detection	**Major Applications** · Magnetic Compass · Munitions fuzing · Mineral Prospecting	**Major Applications** · Noncontact switching · Current measurement · Magnetic memory readout
Most Common Sensors · SQUID Gradiometer · Optically pumped magnetometer	**Most Common Sensors** Search-coil magnetometer Flux-gate magnetometer Magnetoresistive magnetometer	**Most Common Sensors** · Search-coil magnetometer · Hall-effect sensor

Figure 4 - Categorization of magnetic sensor applications

Likewise, sensor technologies are often classified strictly by the magnetic field that they are able to detect. Various types of sensor technologies exist, including: magnetometers (search-coil, flux-gate, optically pumped, nuclear-precession, SQUID, magnetoresistive, and fiber-optic), hall-effect, magnetodiode, magnetotransistor, and magneto-optical. Figure 5 [15] shows the detectable field ranges for these magnetic sensor technologies.



*Note: 1T = 10^{4}G

Figure 5 - Detectable field strengths for various magnetic sensing technologies

A magnetoresistive magnetometer was chosen as the magnetic sensor to use based up the dynamic range of the technology, the resolutions that are achievable with the technology, and cost. One possible selection of such a sensor is the HMC 1043 magnetoresistive magnetometer [16]. Specifications for this sensor can be seen in Table 2.

Table 2 - Honeywell HMC1043 Sensor Specifications

Condition	**Min**	**Max**	**Unit**
Operating Temperature	-40	120	Celsius
Magnetic Field Range	-6	6	Gauss
Source Voltage	1.8	10	Volts
Bandwidth	0	5	MHz
Resolution	120		μGauss

These specifications from this sensor will be used to design and develop a suitable sensor network to determine position and orientation for the tracking system.

4.3 Magnetic Sensor Network

Background information suggests that pure DC tracking is not feasible because there can be no way to distinguish between the magnetic source and the magnetic field of the Earth. This statement implies that both are in the same three-dimensional space for an extended period of time. What if, however, the source is in constant motion and the area of the Earth's field covered by the source changes with time? This can be accomplished by creating a sensor network much larger than the region covered by the source. This is depicted in Figure 6.

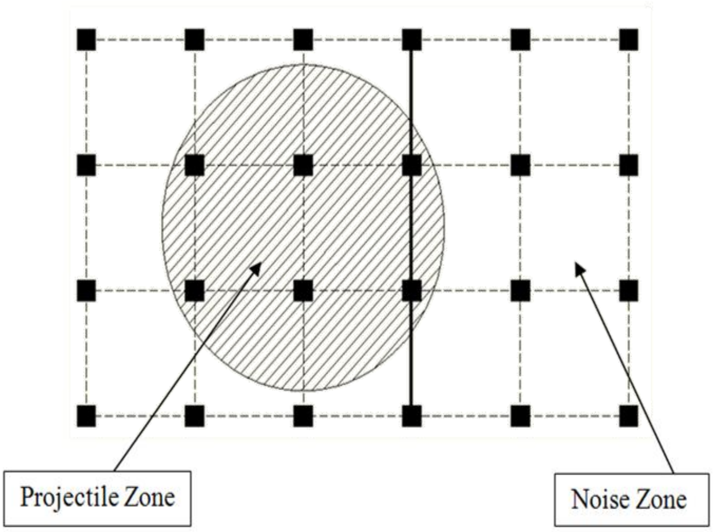


Figure 6 – Zone of the sensor network

As seen illustrated above, the network can be divided into two zones, the projectile zone and the noise zone. The projectile zone accounts for all the sensors that are within the maximum detectable distance of the magnetic sensor, and the noise zone are those sensors not within the detectable distance. Figure 7 shows the projectile moving in time.

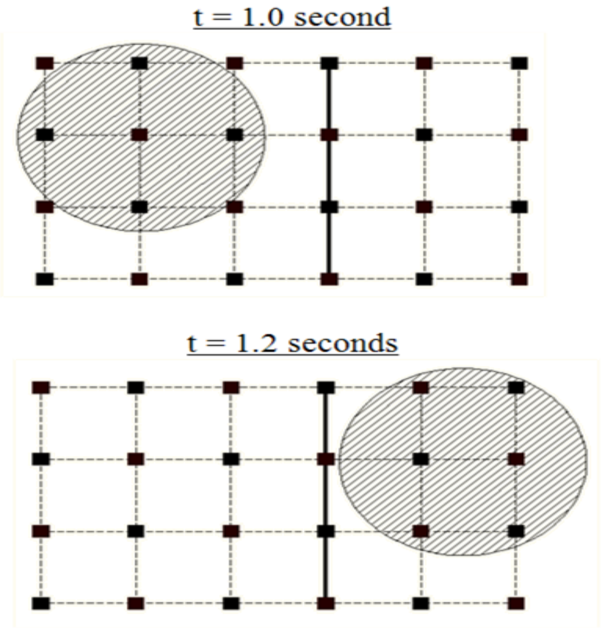


Figure 7 – Possible magnetic projectile path between 1.0 and 1.2 seconds

In the two hundredths of a second between the first and second instance, the source is able to travel completely out of the first projectile zone, and into the noise zone. This process would be similar to that of a pulsed DC source (have a signal once instance, and then having it disappear during the next instance). This process would occur for a high speed projectile moving across a region much greater than the detectable distance of the source.

The next step is to determine the type and spacing of the magnetic sensor. Because magnetic fields extend in three-dimensions, three orthogonal magnetoresistive sensors will need to be used to detect x, y, and z directions. The Honeywell sensor (described above) has exactly this in a single package. Given these sensor specifications, namely the resolution of 120 µGauss, and the equations of a magnetic disc, the maximum detectable distance (under perfect conditions) can be calculated. This is show in the plot in Figure 8.

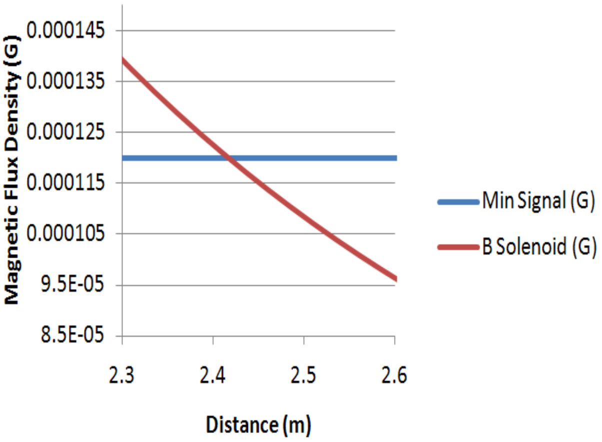


Figure 8 - Scaled graph of magnetic flux density versus distance for a permanent magnetic with remanent Br = 13.2 kG

This figure shows that the maximum detectable range is approximately 2.4 m for a 13.2 kGauss magnetic source. Again, this is only in ideal conditions. For design purposes, scaling the distance down will help reduce error when ambient and other environmental magnetic noises are added to the system. The system, as it will be designed will have a sensor spacing of approximately 3 ft in hopes to reduce experimental error. The system developed will use 24 of these sensor packages in order to cover the sensor network region as seen in Figures 6-7.

4.4 Ambient and Environmental Noise

The two types of magnetic noise that this system will need to address are environmental (caused specifically by the Earth’s magnetic field and other stationary sources, including building, power sources, etc.) and ambient (caused by stray magnetic fields entering and exiting the sensor network region. Both types will have unique, drastic effects on the tracking system ability to determine position and orientation. Environmental magnetic noise will constantly affect the tracking system during all phases of operation. The basis for this type of noise is the ELF/VLF (extremely low frequency/very low frequency) of the Earth’s magnetic field. Extensive research has been performed to measure and map the natural noise floor of the Earth [17]. Data gathered in the United States (Colorado and California) suggest that the dynamic range, from 1 Hz to 100 kHz, of the natural noise floor shows the maximum horizontal flux density to be on the order of 10^{-7} G/√Hz and decays by approximately 10 dB per decade [18]. Given the maximum resolution of the proposed magnetometer is 10^{-4} G, the natural noise floor should contribute very little to measurement error.

Ambient, or stray, magnetic noise will be a large contributor to magnetic interference both because of proximity to the sensor, and strength. This type of noise will be unpredictable as to the time, place, and strength of the interference and will have to be compensated for in a different manner, which includes data and signal processing, as well as position and orientation estimation. Two methods will be implemented to compensate for these different types of magnetic noise. The first method considers that the gradient of the environmental magnetic field over the entire sensor network is constant. This argument proposes that the sensor network is but a point on the Earth’s magnetic field. This assumption allows for a constant value of the Earth’s magnetic field in both the projectile zone and noise zone of the system. The second method assume that the sensor network has memory, and is able to recall the magnitude the magnetic noise so it can be used to remove that noise from the position and orientation estimation. Both of these methods would be programming / software additions to the tracking system.

4.5 Summary

The magnetic tracking system proposed here includes a permanent magnetic source (simulations use a 13.2 kG neodymium magnetic) and a magnetoresistive magneto-meter sensor network. The sensor networks will then be connected to a high speed data acquisition system to poll the sensors, signal conditioners to filter the data, and optimal estimation equations (discussed in later work) to determine the position and orientation in three-dimensional space. A diagram of this system can be seen in Figure 9.

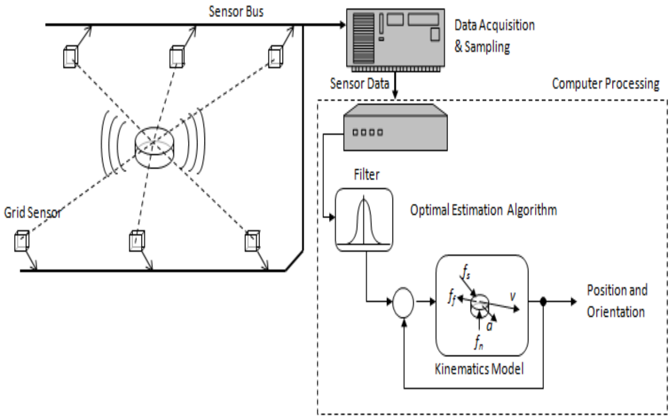


Figure 9 – Diagram of high speed magnetic tracking system

IV. CONCLUSION

This paper has addressed tracking high speed magnetic sources in three-dimensional space. A magnetic source was describes and ideal characteristics were addresses. From this, a permanent magnetic source was selected. Requirements for a magnetic sensor were described and a solution that works well in conjunction with the source was recommended. Methods for recognizing and accounting for environmental and ambient magnetic noise have also been addressed. Although not experimental tested, computer simulations, experimental apparatus, and theory support the tracking system proposed in this paper. Further development will focus primarily on the data acquisition system, signal conditional, and equations to determine position and orientation. Additionally, calculations and simulations will aide in determining and evaluating magnetic noise. Once computational data has been derived and is acceptable, a similar experimental system will be built and tested.

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