Novel Magnetic Projectile Tracking Methodology Using a Single-Axis, Coplanar Sensor Network

Andrew D. Lowery, James E. Smith

Abstract—Near-field magnetic principles and properties have been well studied and are used in a plethora of modern applications, ranging from medical applications to audio and video processing, and magnetic tracking. Most of these tracking systems, however, employ complex sources and/or receivers. It was the purpose of this research to propose a methodology that can determine the three-dimensional position and orientation of a permanent magnetic source; the position and orientation to be determined by information reported by a network of single-axis, coplanar magnetic sensors. The methodology developed uses a computationally simplistic center-finding algorithm to determine position (x- and y-axis) based on the unique geometry of the B-field of the magnetic source at any point in three-dimensional space. Two degrees of orientation, elevation and rotation, were calculated from the position and the reported values of the magnetic sensors. The z-axis position was then determined given the analytical model and the other calculated values. Two experimental tests verified the theoretical predictions of this hypothesis; a rotational test apparatus was used to verify two-dimensional position and orientation, while a linear test apparatus verified position in three dimensions. The same magnetic source was used, while changing the orientation for each. The mean overall error for these tests was less than 2.5% on the constructed experimental apparatus. These results suggest that this novel methodology is credible for magnetic detection and tracking.


I. INTRODUCTION

Current magnetic tracking applications exist for a variety of applications. These active systems are made using both AC and pulsed DC magnetic fields. Generally, AC systems have high resolution and accuracy, but perform very poorly in the presence of conducting magnetic materials such as carbon steel and iron alloys [1]. It is often for this reason that DC systems are employed [2]. It has been suggested that pure DC systems are not always feasible because there is no easy or reliable way to account for the presence of the Earth’s magnetic field [3]. The traditional solution to this problem is through the use of pulsed DC magnetic sources. Pulsed DC tracking has the benefit of reducing eddy currents in relatively close proximity to magnetic materials, thus increasing its overall accuracy [3]. For this novel implementation of a magnetic projectile location system [4], position and orientation will be determined by using a network of single-axis magnetic sensors and a priori knowledge of the geometry of the magnetic flux density (B-field) of the source. This system uses an algorithm that takes advantage of the B-field geometry, creating a linear solution, thus reducing the amount of computation time necessary for location and tracking applications compared to complex iterative solutions methods.

II. MOTIVATION FOR LOCATION SYSTEM

Because of the variety of uses of magnetic sources and magnetic sensing devices currently available, the magnetic tracking systems have a host of possible embodiments that require a large amount of magnetic data/sensors. The proposed system provides a new methodology that reduces complex sensor requirements as well as computational time. Possible uses for this novel design are described in the sections below.

A. Sporting Event Tracking and Goal Detection

Often, improper or inaccurate calls by a scoring official also result in a delay in the game and loss of momentum for both the teams and the spectators. To facilitate the calls of the officials, video equipment and the availability of video play-back can aid in the decision making process. [5], [6] In some applications such as hockey [7], [8], high speed video cameras blanket the rink, covering the visible ice from as many angles as possible. Unfortunately, even all of this visual monitoring equipment can be interfered with, which is particularly true when the field of view is obscured by players or their equipment. Additionally, the speed of the puck and the actions and interactions of the skaters surrounding it can easily hide the progress on, or near, the goal line. Attempts have been made in the past to track the puck on the ice. [9] This was mainly for television viewers to be able to locate the puck while in action. Previous methods attempting to perform goal detection were based solely on visible recognition, and therefore were not accurate enough for goal tracking because the puck is often occluded by the goal keeper or other players. The novel method of using magnetic sources and sensors described in this document will propose a tracking system that is not dependant on visual interpretation.

B. Tracking and Security for Retail and Merchandise

Retail and merchandise theft account for billions of dollars of consumer products every year. Several methods using magnetic locator chips exist for detecting stolen merchandise. Each of these requires a special case, and/or removal or
deactivator tool. Much like magnetic security devices that are used to protect expensive electronics in stores today, a small magnetic source could be embedded in product packaging to be used to detect concealed merchandise leaving the premises, as well as its movements from the warehouse, to store, to consumer. Additionally, a small scale magnetic system could be used to track merchandise in-store or in-warehouse for security or inventory purposes. Although there will not be enough information to uniquely identified specific products, this system could be used to quickly identify packages marked as expensive, perishable, dangerous, or otherwise differentiable. A simple implementation includes a small, inconspicuous magnetic source network that could be deployed around doorways, thresholds, or in specific areas of warehouses or storage areas with the ability to detect when merchandise enters and exits. This sensor network could be connected to a data acquisition system capable of detecting a magnetic signal as small as a few hundred milligauss. Information about the product and number of products could be then directed to the store's inventory management system.

C. Tracking and Mapping For Medical Applications

Currently, there is a push for enhanced medical devices, especially those that aide in unlocking the mysteries of the human body. A magnetic source could be used to track bodily functions or map organs such as the intestinal tract or blood stream. Again, due to the nature of the magnetic field, and its ability not to be limited to line of sight, tracking magnetic sources in the body will be much like tracking outside of the body. Additional modifications will be needed for inter-body tracking. The first and foremost will be the size and strength of the magnetic signature. The size of the source will be dictated by the application, “mili” scale for intestinal tract and “nano” scale for blood / vein mapping. Because of the size / strength relationships between most magnetic materials and the strength of the magnet will also need to be reduced. Current magnetic resonance imaging (MRI) machines use magnetic fields between 4.7 kG and 47 kG [10], but these fields are exterior to the body and are thus reduced over distance. Although the body is able to tolerate large static magnetic fields, it does not fare as well with dynamic magnetic fields [11]. Clarity and precision will be critical in this embodiment. Since the patient will be confined to the examination table, the magnetic sensors will only need to have a vertical range of the width of a body (approximately 18 in), instead of multiple feet as would be needed for large scale object tracking? In order to ensure needed details, the sensor network, or sensor substrate, will need to be denser. It may be necessary for several hundred sensors to be used and in varying configurations for suitable clarity.

III. REVIEW OF MAGNETIC LOCATION SYSTEMS

Several applications for tracking an object’s position and orientation have been considered. Most of these applications used some type of small perturbation algorithms for tracking, with different types of sources and sensors to do the job. Most of the systems also require elaborate, multiple axis receivers. Although successful at tracking relatively slow moving object over small ranges, none of the addressed systems are able to track objects over larger distances. Half of the systems examined also require both a powered source and receiver. Table 1 compares the results in this section to the desired results of the proposed system.

The intent of the proposed system [4] is to maintain the detectable range and accuracy of the previously reviewed systems (Table 1) while using a simple permanent magnetic target moving in three-dimensional space across a grid of one-dimensional magnetic sensors. While most systems presented here are able to track and locate objects within the range of inches, the proposed system will track an object up to an approximate range of 2 to 3 ft, limited primarily by the Earth's field acting as a noise floor. A successfully system will include a sensor package capable of detecting a large magnetic field, ranging from the kilo-Gauss range (to detect a nearby magnetic source) to the milli-Gauss range (to detect perturbations in the Earth's magnetic field). A magneto resistive sensor will be shown to be adequate for this job. A source that is “strong enough”, or one that has a high remanent magnetism, is also needed. Rare Earth magnets, such as a Neodymium (NdFeB) magnet, will be shown to be well suited for this task; their use is preferred since they require no additional excitation energy.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Sensor Type</th>
<th>Source Type</th>
<th>Range</th>
<th>Sampling Freq.</th>
<th>Accurac y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Madawala and Pillay [12]</td>
<td>Hall Effect</td>
<td>Coil windings</td>
<td>1 in</td>
<td>1 Hz</td>
<td>± 0.59 in</td>
</tr>
<tr>
<td>Raab et al. [13]</td>
<td>Magneto resistive</td>
<td>3-axis magnetic dipole</td>
<td>39 in</td>
<td>30-120 Hz</td>
<td>NR</td>
</tr>
<tr>
<td>Schlager et al. [14], [15]</td>
<td>Hall Effect</td>
<td>Permanently Magnet</td>
<td>5.5 in</td>
<td>50 Hz</td>
<td>± 0.59 in</td>
</tr>
<tr>
<td>Sherman et al. [16]</td>
<td>Hall Effect</td>
<td>NdFeB Magnet</td>
<td>12 in</td>
<td>100 Hz</td>
<td>± 0.21 in</td>
</tr>
<tr>
<td>Proposed System [4], [17]</td>
<td>Magneto resistive</td>
<td>NdFeB Magnet</td>
<td>24-36 in</td>
<td>&gt; 120 Hz</td>
<td>~ 0.2 in</td>
</tr>
</tbody>
</table>
IV. DESCRIPTION OF NOVEL MAGNETIC LOCATION SYSTEM

The magnetic source that is used is a simple permanent magnet. Because magnetic fields of simple sources at distances greater than the magnet from the point of measurement resemble a magnetic dipole, the dipole equation will serve as a starting point for developing a magnetic model. This magnetic dipole equation was introduced as (1):

\[ B(m, r) = \frac{B_r}{2} \left[ \frac{3\hat{r} \cdot (\hat{r} \cdot m) - m}{|\hat{r}|^2} \right] + B_{EARTH}, \tag{1} \]

where \( B \) is the magnetic flux density, \( B_r \) is the surface remnant magnetization, \( B_{EARTH} \) is the magnetic flux density of the Earth, \( r \) is the vector distance between source and measurement, \( \hat{r} \) is a unit vector along \( r \), \( \mu_0 \) is the free space permeability, and \( m \) is the magnetic dipole moment. Given the generalized form of the magnetic flux density, (1), an expression is derived using only the \( z \)-axis component of the magnetic flux density, (2), and the definitions for rotation and elevation, shown in Fig 1.

Fig 1 - Definition of Model Coordinate System

This expression for magnetic flux density yields a unique solution for a magnetic projectile relative to the stationary sensor network at any three-dimensional position \((x, y, z)\), and with any orientation \((\theta, \phi)\). This can be seen with plot data shown in Fig 2. This uniqueness allows for the three-dimensional position and orientation to be determined using a simplified, linear method.

\[ B_z(x, y, z, \theta, \phi) = \frac{B_z}{2} \left[ \frac{3(x \sin(\theta) \cos(\phi) + y \sin(\theta) \sin(\phi) + z}{\cos(\theta)} \right] + B_{EARTH}, \tag{2} \]

In order to determine the position, a center finding algorithm was developed, that used the intersection of surface normal vectors. Fig 3 (top) shows the same data in a two-dimensional plot, with a clear intersection at the location of the magnetic source. However, Fig 3 (bottom), shows the same data in a two-dimensional plot, with a clear intersection at the location of the magnetic source.
In order to determine these quantities to calculate position and orientation, a sensor network layout must be constructed. To determine surface normal vectors, three sensors must be used. A triangle layout, Fig 5, was implemented. Each magnetic sensor is single (z) axis. These "clusters" are then combined to form a magnetic sensor array, such as the one seen in Fig 6. This sensor network is capable of measuring both the flux density associated with the permanent magnet, and the flux density associated with the Earth's magnetic field.

A permanent magnetic disk was passed over this sensors network at elevations of 0°, 15°, 30°, 45°, and 60°, and data was collected and analyzed. Experimental results for the rotational (circle) case can be seen in Fig 8 and Fig 9, comparing an actual trajectory with the calculated trajectory from the proposed location system. Likewise, experimental results from the linear case can be seen in Fig 10.

A sensor network, similar to Fig 7, was constructed to verify the claim of the proposed system. The experimental apparatus was used to test two magnetic projectile trajectories: a circle in two-dimensions and a line in three-dimensions. These two scenarios allow for the system to be exposed to three dimensions of position, and two of orientation, as stated in the goal.
VI. CONCLUSION

Presented here is a novel implementation of a "pure-DC" magnetic location and tracking system. This paper shows a methodology that implements a single-axis magnetic sensor network to be used to determine three-dimensional position and orientation of a magnetic projectile. These results show that using the unique geometry of the B-field to calculate the position and orientation of a magnetic source is a viable option to track magnetic objects in three-dimensional space. This contribution has shown that it is not necessary to gather multiple dimensions of magnetic sensor information to determine a magnet's position in free-space. It is possible to track and locate the three-dimensional position and orientation of a permanent magnetic source (with known or simplified magnetic flux geometry) with only a single-axis magnetic sensor network. While this system works well with three-dimensional tracking problems, it is also capable of two-dimensional tracking with less computational effort. Using this approach, position and orientation can be described solely based on the location and B-field magnitude of each single-axis magnetic sensor.

REFERENCES


Table 2 - Summary of Experimental Results for Rotational (Circle) Case

<table>
<thead>
<tr>
<th>Angle (°)</th>
<th>Mean Overall Error (%)</th>
<th>Max Overall Error (%)</th>
<th>Mean Difference (Rotation, °)</th>
<th>Mean Difference (Elevation, °)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.55</td>
<td>4.90</td>
<td>13.50</td>
<td>2.19</td>
</tr>
<tr>
<td>15</td>
<td>1.10</td>
<td>2.78</td>
<td>13.79</td>
<td>18.72</td>
</tr>
<tr>
<td>30</td>
<td>1.08</td>
<td>3.18</td>
<td>13.85</td>
<td>22.65</td>
</tr>
<tr>
<td>45</td>
<td>1.40</td>
<td>4.63</td>
<td>13.92</td>
<td>23.16</td>
</tr>
<tr>
<td>60</td>
<td>2.41</td>
<td>6.37</td>
<td>13.76</td>
<td>27.95</td>
</tr>
</tbody>
</table>

Table 3 - Summary of Experimental Results For Linear Case

<table>
<thead>
<tr>
<th>Angle (°)</th>
<th>Mean Z-Axis Error (%)</th>
<th>Mean Overall Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.24</td>
<td>1.40</td>
</tr>
<tr>
<td>15</td>
<td>0.19</td>
<td>1.38</td>
</tr>
<tr>
<td>30</td>
<td>0.15</td>
<td>0.87</td>
</tr>
<tr>
<td>45</td>
<td>0.19</td>
<td>1.13</td>
</tr>
</tbody>
</table>

*Note: 60° case was not experimentally tested

Additionally, this novel location network leads to an overall system that can locate, and track, at computational speeds much faster than iterative solvers. The computational times of the proposed location system are shown in Table 4. These results are based on the solution to the linear test case, with a sample size of 500. The sample iterative process used MATLAB's nonlinear, least squared solver with a tolerance of 1e-3 and the model in Eq. (2) with 5 sensors as an input which converged in 48.87 sec, and converges in at most 6 iterations (given good initial conditions). The proposed methodology calculated a solution in 2.62 sec for the same data set. These results show an increase in computational speed up to 1865% using the smallest number of clusters (5), and 274% increase using the number of clusters (15) as used in this configuration.

Table 4 - Computation Speeds of Proposed System vs. Iterative Solver (For A Sample Size of N = 500)

<table>
<thead>
<tr>
<th>No. of clusters</th>
<th>Proposed system (sec)</th>
<th>Speed increase (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>2.62</td>
<td>1865</td>
</tr>
<tr>
<td>10</td>
<td>8.65</td>
<td>565</td>
</tr>
<tr>
<td>15</td>
<td>17.82</td>
<td>274</td>
</tr>
</tbody>
</table>

Fig 10 - Position for Linear Test Apparatus (Θ = 0°, 15 Clusters)

Table 2 and Table 3 show a summary of all experimental testing for both cases. Mean overall error was less than 2.5% for all data sets. Mean differences in rotation and elevation are large; but can be attributed to the few number of magnetic sensors in this test apparatus. In practice, this error can be reduced when the number of magnetic sensors implemented is increased. [4]


AUTHOR’S PROFILE

Andrew D. Lowery has received degrees of Doctor of Philosophy in Engineering (2012), Masters of Science in Mechanical Engineering (2006) and dual Bachelors of Science degrees in Computer and Electrical Engineering (2004) from the College of Engineering and Mineral Resources at West Virginia University (WVU). Currently, he is a post-doctoral research fellow in the Mechanical and Aerospace Engineering department at WVU and a Research Assistant at the Center for Industrial Research Applications at WVU where his research focuses primarily in the areas of control systems and systems engineering. Dr. Lowery has been associated with various projects funded by federal agencies (including DoD, DoE, and DARPA) while also having multiple opportunities to teach engineering students at the undergraduate level.

During his educational career he has participated in research in the areas of design and controls, electromagnetics, and engineering education, resulting in peer reviewed publications, including nine conference proceedings and two journal or bound papers. Dr. Lowery is a member of the Institute for Electrical and Electronics Engineers (IEEE), Society of Automotive Engineers (SAE), and Sigma Xi, The Scientific Research Society.

James E. Smith received his Bachelor of Science and Master of Science degrees in Aerospace Engineering and Doctor of Philosophy degree in Mechanical Engineering from West Virginia University (WVU), Morgantown, West Virginia, USA in 1972, 1974, and 1984, respectively. He is currently the Director of the Center for Industrial Research Applications (CIRA) at West Virginia University, where he is also a Professor in the Mechanical and Aerospace Engineering (MAE) Department. He has taught at the University since 1976, before which he was a Research Engineer for the Department of Energy (DOE). He was the 2009 SAE International President and Chairman of the Board of Directors which afforded the opportunity to travel to the mobility centers of the world. During his 40-plus-year scientific career, he has been the principal and/or co-principal investigator for various projects funded by federal agencies (Tank-Automotive Armaments Command (TACOM), Department of Defense (DOD), HEW, Department of Transportation (DOT), US Navy, Defense Advanced Research Projects Agency (DARPA), and Department of Energy (DOE)), international corporations, and numerous US corporations. The work in these projects has resulted in the publication of 172 conference papers and 60 journal or bound transaction papers. This work has resulted in the granting of 31 United States Patents and numerous foreign patents on mechanical and energy-related devices. Dr. Smith is a member of American Institute of Aeronautics and Astronautics (AIAA), Society of Automotive Engineers (SFAE) International, American Society of Mechanical Engineers (FASME), International Society for Computers and Applications (ISCA), American Society for Engineering Education (ASEE), Institution of Mechanical Engineers (FIMechE), and International Society for Instrumentation Engineers (SPIE).