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Evaluation of Magnetic Markers as a Position Reference System For Ground Vehicle Guidance and Control

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ABSTRACT

This report contains an evaluation of the sensing techniques and implementation issues of magnetic sensing as a position reference system. The field patterns of sample magnetic markers were first measured to illustrate the basic characteristics of such systems. Several sensing approaches were explained and compared with regard to their functioning principles and sensitivity to measurement variations. Three particular algorithms were discussed with illustrations of respective mapping methods. Robustness and sensitivity of the sensing methods, when subject to signal noises and parameter variations, are desirable features.

A framework for dealing with technical limitations and objectives is outlined. The constraints and preferences of sub-systems and the corresponding issues are listed for further evaluation of described sensing systems. The optimization of such systems can only be accomplished by building the appropriate evaluation models for each component and the overall system. With the increasing deployment of magnetic sensing systems for position reference, these subjects deserve elaborated studies and thorough analysis.

KEY WORDS:

Magnetic, Sensing, Position Reference, Ground Vehicle Guidance and Control

EXECUTIVE SUMMARY

In advanced vehicle control and safety systems, position measurement is an important link for the identification of vehicle locations, such as lateral position relative to a lane or a desired trajectory. Technologies developed for such purposes include electrically powered wire, computer vision, magnetic sensing, optical sensing, inertia navigation and global positioning systems. This report focuses on magnetic sensing systems that have been developed at PATH during the last decade and used for ground vehicle control and guidance.

This report contains evaluation studies from several areas:

(1) The magnetic fields from a sample magnet are used to illustrate the characteristics of their patterns as the basis for detection and position identification.
(2) Magnetic markers of various sizes and sources are measured to show the potential variations among the choice of markers.
(3) The significance of magnetic fields in signal processing is explained with a preliminary review of sensing algorithms.
(4) The basic rules and guidelines in selecting and installing markers in system implementation are given based on experiences accumulated from PATH projects.
(5) The issues and related implications in the optimization of marker systems are presented.

With successful demonstrations in several applications and different operating environment, position measurement using magnetic markers have proven to be an appropriate candidate for ground vehicle guidance and control. For system-wide deployment of similar technologies, the subject deserves further investigations into broader issues such as magnet size, materials, and spacing optimization, system durability and total costs in conjunction with continual improvements in the accuracy and robustness of sensing capabilities.

1.0 Background

Magnetic sensing is one promising technology that has been developed for the purposes of position measurement and guidance, especially notable for applications in advanced vehicle control and safety systems (AVCSS). In recent years, the California PATH program (Partners for Advanced Transit and Highways) has deployed the magnetic marker system in conjunction with its experimental vehicles in a number of international and national demonstrations [1-5]. These experiments successfully illustrated the potential of this fundamental element for advanced transportation systems in activities such as the 1997 National Automated Highway System Consortium (NAHSC) Demo, the snowplow projects in California and Arizona, and Japan Smart Cruise 21.

In the positioning reference system demonstrated by PATH, magnetic markers with a size of 2-3 cm diameter and 10 cm long are installed just under the surface of roadway pavement. Figure 1 shows a typical marker and its orientation on a roadway before insertion into a hole in the pavement. The magnetic fields generated by these markers are detected by magnetometers mounted under the bumpers of test vehicles.

Figure 1. An exemplar marker before insertion into a hole in the roadway pavement

In this report, the sensing concept is first illustrated in Section 2 by introducing the magnetic patterns produced by an exemplar marker. Subsequently, measurements taken from a variety of markers of different sizes and manufacturers are given in Section 3 to compare their relative strengths.

The applicability of magnetic sensing for position identification systems hinges on the performance capabilities, such as accuracy, working range, and robustness. The performance in turn depends on the reliability of sensing algorithms designed for detection and recognition of magnet locations. The magnetic fields and related complications in sensing algorithms are discussed in Section 4.0.

For a system implementation, there are certain preferred characteristics and guidelines in selecting and installing markers. These basic rules and guidelines are described in Section 5. The increasing deployment of magnetic sensing systems has stimulated continuing efforts to further explore the usage of these technologies and the issues surrounding the development of such systems. Among those issues are the installation of magnets in a cost-effective way, the durability of magnet and pavement jointly, and the optimization of system configuration on roadway and vehicles. The paper concludes with a discussion of these concerns in Section 6.

2.0 Magnetic Patterns of Exemplar Markers

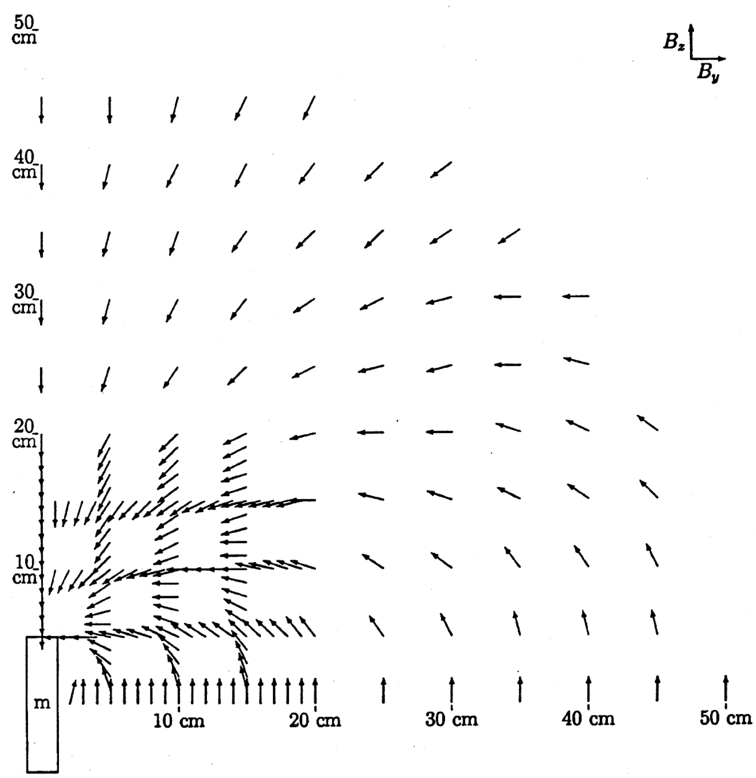

Figure 2. Magnetic Flux around a Dipole Marker

Figure 2 illustrates the flux patterns of the magnetic fields around a dipole, such as one created by a cylindrical marker shown in Figure 1.

In this section, the experimental data collected from marker tests are presented for a comprehensive analysis of the magnetic fields. The data was collected from a static test on a bench table. The sample marker is a ferrite magnet (ceramics made primarily from iron and boron with a small amount of strontium) in a cylindrical shape with a diameter of 2.5 cm and a length of 10 cm. The long axis of the cylinder is placed perpendicular to the surface of the bench table. The measurements took place with a magnetometer at several different heights from the surface of the table to acquire a representative map of the magnetic field. For each sensor height, the measurements were taken with and without the marker in place so that the background earth field can be subtracted. For illustration, the data with the sensor at 27 cm high are shown below.

Figures 3 to 5 are the three-dimensional plots for each component in three orthogonal axes with the sensor at a height of 27 cm from the upper end of the marker. The longitudinal component is parallel to the line of magnet installation, the vertical component perpendicular to the surface, and the lateral component perpendicular to the other two axes. The plots are generated with the origin at the location of the marker.

Notice how the three components change over space. The lateral field is opposite in sign and symmetric in magnitude on two sides of the marker. The lateral component rises from zero at the center of the marker and reaches its peak at a distance about 15 cm from the marker, then gradually weakens farther away from the marker. The peak value for the data set in Figure 3 is about 300 milli-Gauss (mG). The pattern of lateral measurements across the marker at any cross-section is similar, but the peak magnitude varies along the longitudinal axis.

The vertical field is the strongest right at the top of the marker, and diminishes to zero at about 40 cm away from the marker. The peak value is about 750 mG for the data set in Figure 4. The vertical field quickly drops as it moves away the marker. Since the vertical field is the strongest component among the measurements near the marker, its use will be significant in identifying the closeness of a marker.

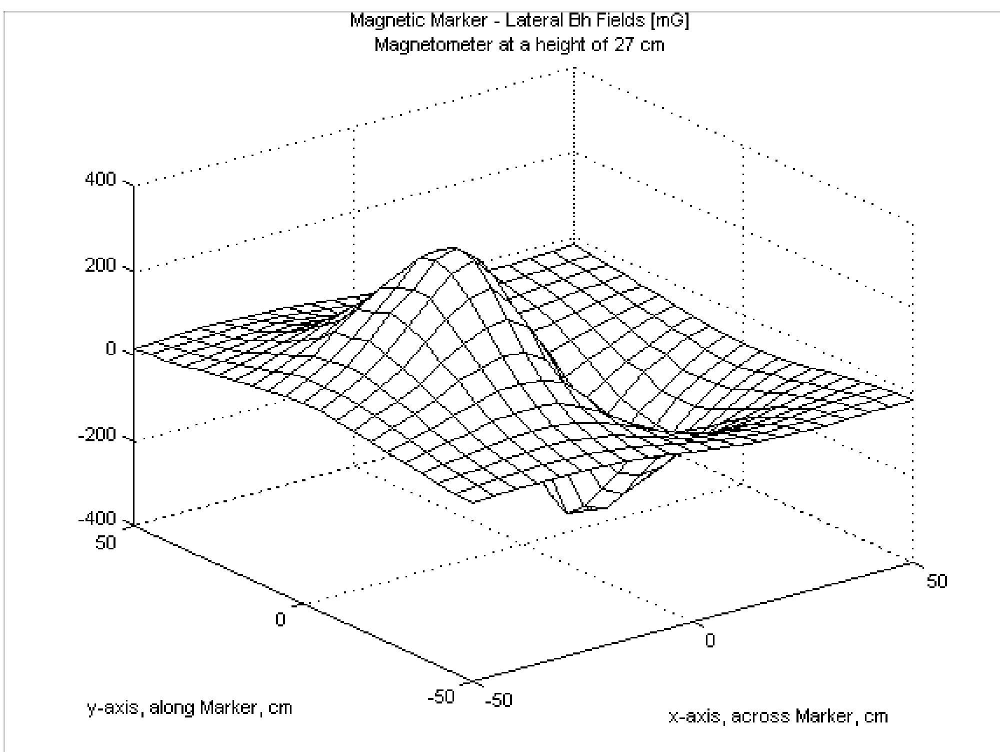

Figure 3. Lateral Component of Magnetic Field of a Marker with Sensor at 27 cm High

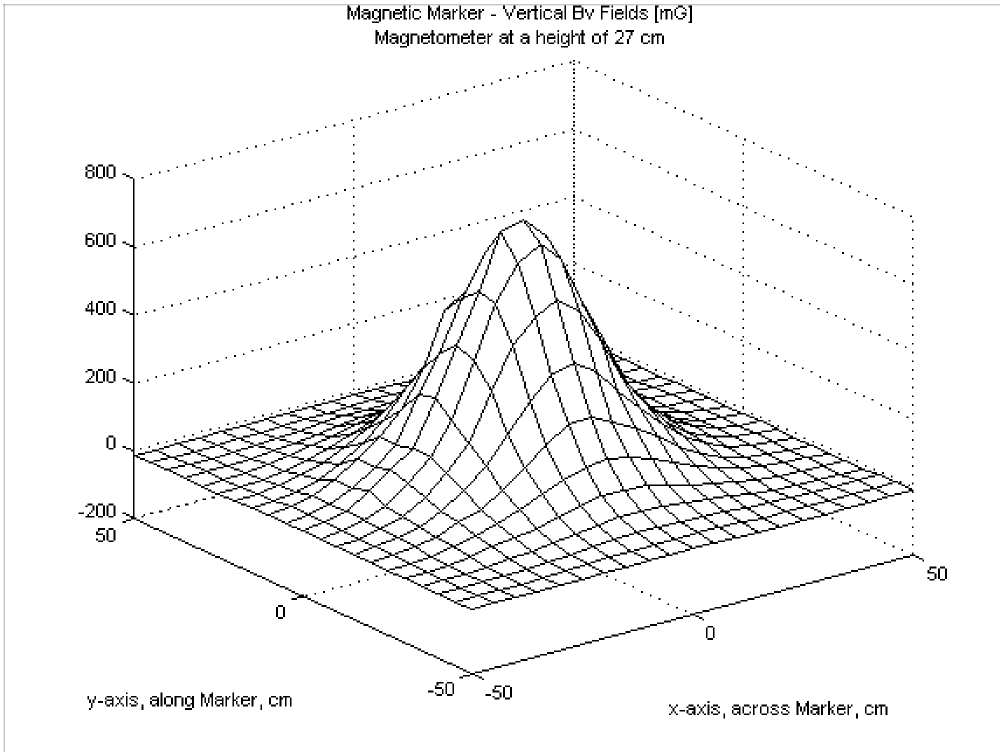

Figure 4. Vertical Component of Magnetic Field of a Marker with Sensor at 27 cm High

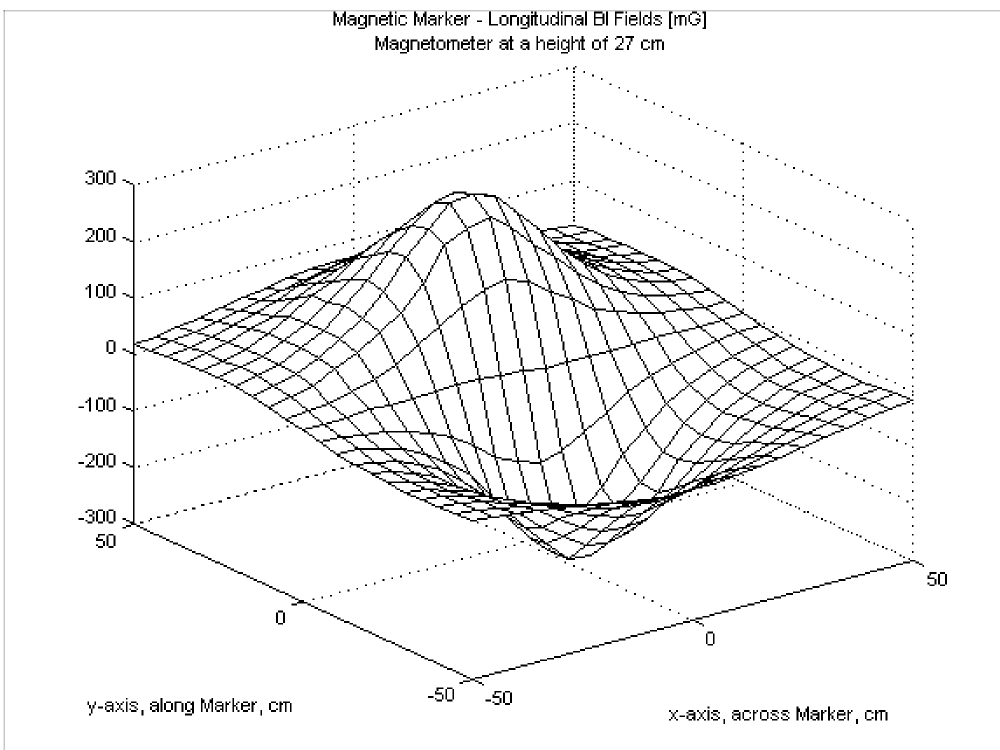

Figure 5. Longitudinal Component of Magnetic Field of a Marker with Sensor at 27 cm High

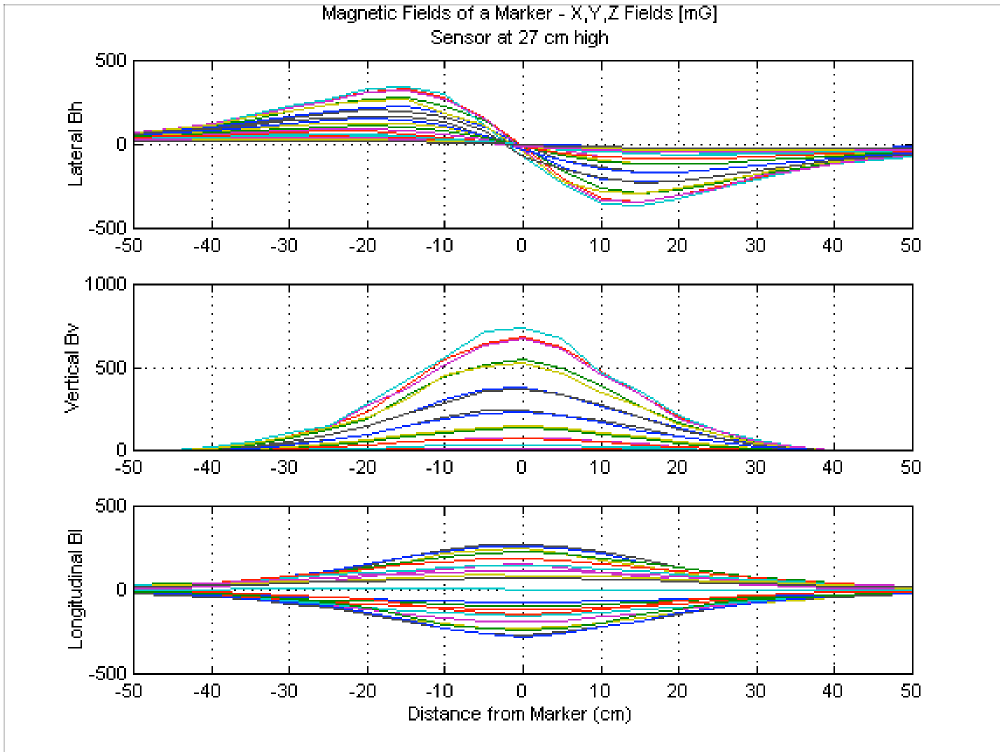

Figure 6. Magnetic Field Components in 3 Axes at Various Distances to a Marker

The longitudinal component reaches its peak at about 15 cm from the marker. The peak value for this data set is about 300 mG. The longitudinal field makes a steep transition near the marker as it changes its sign. This steep transition becomes meaningful in interpreting the point at which a sensor passes through a marker location.

Figure 6 shows the composite curves with data from the three axes plotted along the distance from the marker. Each curve represents the measurements at one cross section along the lateral axis, while multiple curves in each plot represents the measurements at various locations along the longitudinal axis. The transition of the magnetic fields along three axes can be clearly identified.

3.0 Comparisons of Magnetic Fields from Different Markers

Figure 7 shows the magnetic strength of a ferrite marker measured at a sensor height of 27 cm. A typical marker, as shown in Figure 1, actually consists of four one-inch units, which can be separated individually. As depicted in the plot, each additional unit adds a decreasing amount of field strength to the measurements. This is due to the fact that the sensor is placed at the indicated distance from the top of the marker. Each additional marker unit is attached to the bottom of the dipole, as shown in Figure 2, therefore the center of the dipole is further away from the sensor as each additional unit is added. However, it can be noticed that the characteristics and the shapes of these curves remain the same. Thus, as long as the magnetic strength of the marker is great enough for a sensor to detect, the same signal processing approach is likely to succeed in recognizing the position of the magnet.

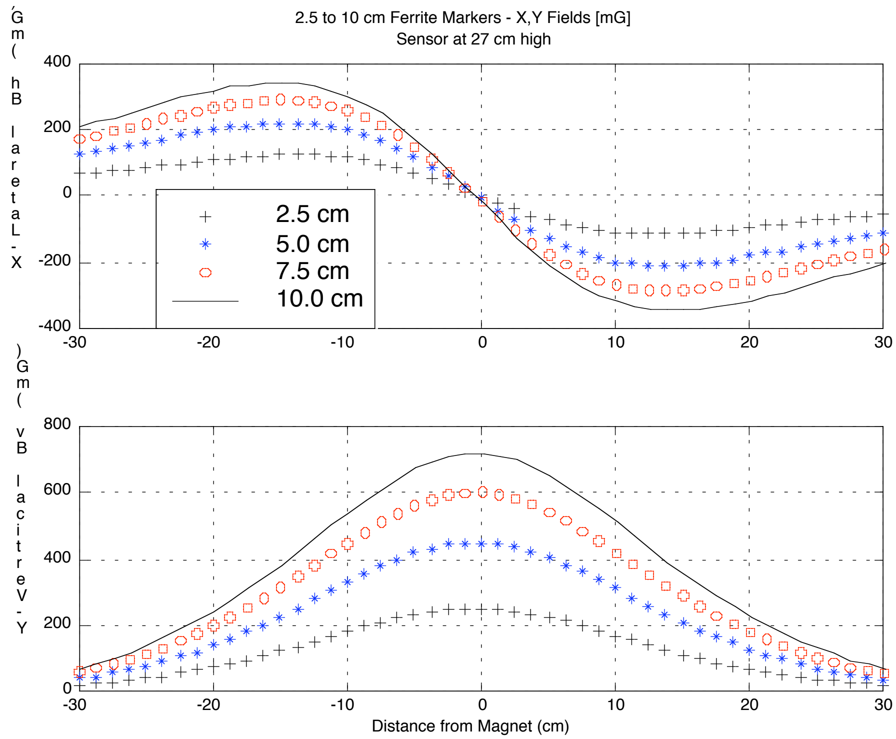

Figure 7. Lateral and Vertical Field Components of a Ferrite Marker of Different Lengths

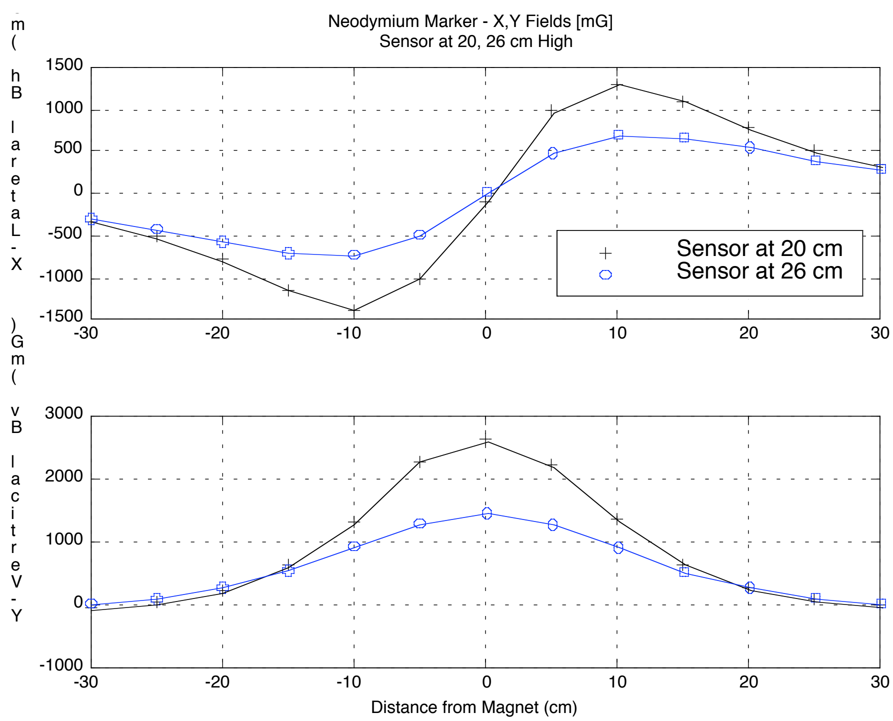

Figure 8. Lateral and Vertical Field Components of a Neodymium Marker

In several system implementations, PATH researchers have found that it is necessary sometimes to install a stronger magnet so that the magnetic signals are more recognizable. These situations arise when there are strong disturbances or noises from the ground, such as bridges with reinforcement structures. For this reason, a Neodymium magnet of 2.5 cm length, rather than the standard ferrite unit shown in Figure 7, was used in these applications. Figure 8 depicts the magnetic fields from such a rare-earth unit measured at two different heights. It can be seen that at a comparable height, the fields from the 2.5 cm Neodymium unit is more than three times stronger than a 10 cm ferrite unit.

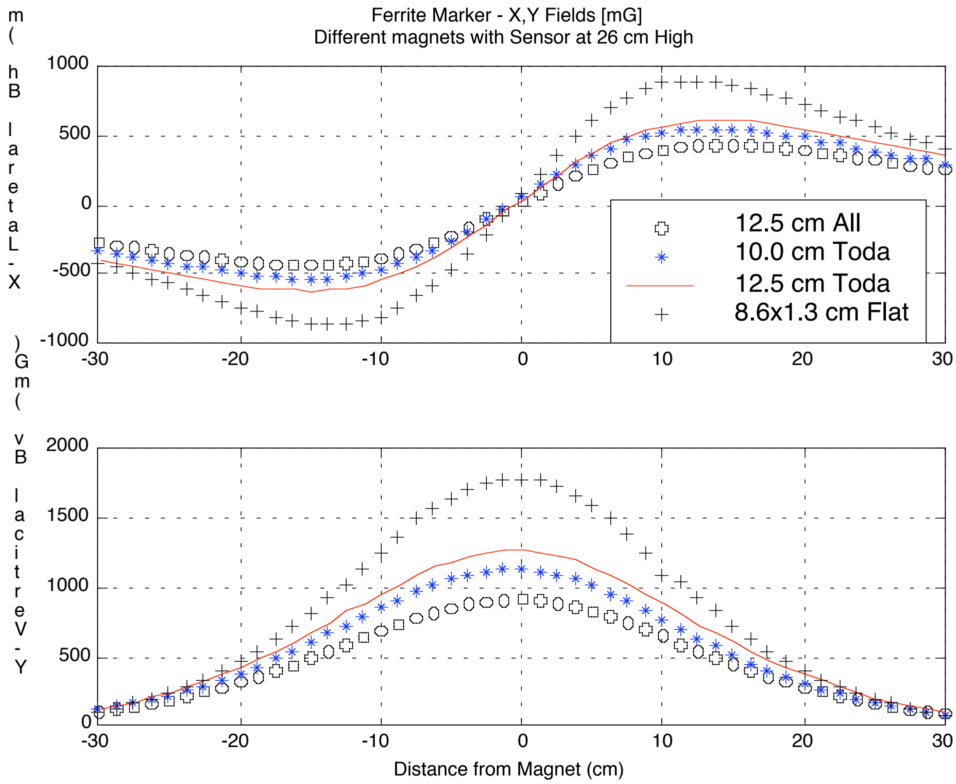

Figure 9. Lateral and Vertical Field Components of Several Different Markers

Figure 9 shows the lateral and vertical magnetic field components of several different markers with measurements taken at a height of 26 cm. It is used to compare the strengths of markers of various dimensions from different manufacturers. A standard PATH marker from All Magnet Inc.[1], of the same materials as those shown in Figure 7 but of a 12.5 cm length, is compared with a marker from Toda[2], another manufacturer. It can be noted that the Toda unit with 10 or 12.5 cm length is stronger than the All-Magnet unit. A flat disk-shaped magnet, with a diameter of 8.6 cm and a depth of 1.3 cm, is also shown in the comparison charts. The flat disk possesses considerably stronger magnetic properties than the others.

[1] All Magnetics, Inc., 930-CS Placentia Ave., Placentia CA 92670, TEL:714-632-1754

[2] Toda America Inc., Woodfield Green Executive Center, 1920 North Thoreau Drive, Suite 110, Schaumburg, IL 60173, TEL:847-397-7060

4.0 Signal Processing and Sensing Algorithms

In this section, several signal processing techniques and sensing algorithms for position identification are presented with a discussion of related technical issues. In general, the signal processing for the described position measurement application involves two tasks: (1) the removal of background fields and noise, and (2) the mapping of processed signals to a position relative to the magnet.

Figure 10 shows the lateral and vertical fields generated by a sample marker at three different heights. The third (longitudinal) axis is not shown since it is similar to the lateral direction, only in a different orientation. It should be noted that the magnetic field of the magnetic marker could be modeled as a cylindrical dipole. We use the experimental measurements for an actual representation. The field strengths decay rather quickly as the measurement point moves away from the magnet.

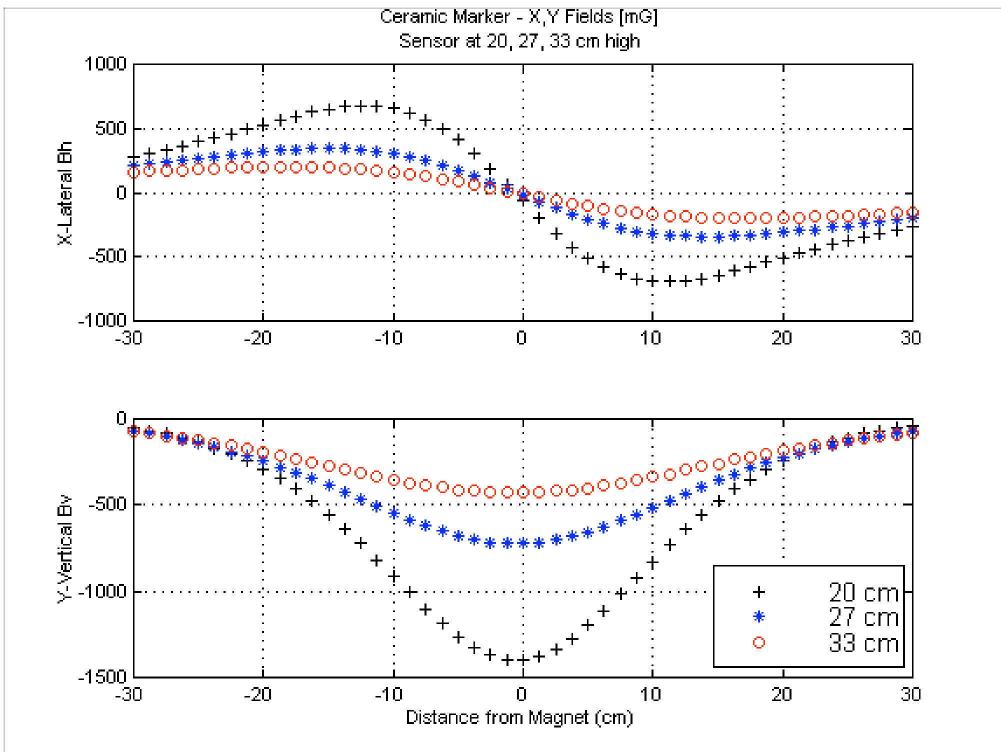

Figure 10 Lateral and Vertical Components of Magnetic Fields around a Sample Marker

There are several sources of measurement noise: earth, AC-generated, and electrical. The largest source of external disturbances comes from the earth, which is documented in a separate report [6]. The earth signals vary with the coordinate axes of the sensor, which changes with the vehicle's attitude and orientation. A second source of noise comes form the alternating fields generated by various motors in the sensor's vicinity, such as vehicle alternator, compressor, pump, fan, and actuators. The knowledge of sensor installation plans and operating characteristics of nearby motors can help identify the nature of these noises. It is also possible to shield AC-generated disturbances by using materials with low magnetic reluctance. The other source of noise arises from electrical fields. They show up as fluctuations in the signals. A low-pass filter can be used to remove much of this noise.

The calculation of the earth field is by no means trivial. Since the earth field changes with the location as well as the vehicle orientation, it does require a real-time estimation. An error in the value of earth field can result in totally incorrect interpretation of the measured fields. Since sensing algorithms are based on the pattern of magnetic fields near the magnet, it is essential to take great caution in estimating the disturbances.

Several approaches have been suggested to take the earth field out of the measured signal, including (1) averaging, (2) peak-valley identification, and (3) differentials between dual sensor measurements. The first method is based on an average of longitudinal data measurements over a number of markers. This is based on the assumption that the longitudinal fields averaged from the magnets will approach zero, thus the remaining average represents the earth disturbance. While it is simple to implement, it is slow to respond to a quickly changing ambient field. The second method utilizes the identification of valleys in the vertical field between magnets, thus reflecting the ambient fields. An interpolation between the previous and the current valley values yields an updated ambient field estimate. The last method uses two nearby sensors to eliminate the common background components by taking the differential between dual sensors. It is based on the assumption that the background fields are approximately the same at the two sensor locations. Some of these techniques will be explained in the following sub-sections.

Once the background disturbances are removed, the remaining portion of the signals represent the fields generated from the expected magnet. From these signals, the distance to the magnet must be determined. Several methods are proposed for this task: (1) Peak mapping, (2) Differential peak mapping, and (3) Vector ratio method.

4.1 Peak Mapping [7]

The magnetic marker system is typically installed with a spacing of one meter or larger between the magnets. Therefore, the measured signal, particularly the strongest vertical component, will likely show a peak-and-valley sequence. However, due to the earth and other ambient disturbances, it is impossible to determine whether the local peaks and valleys in measurement correspond to those signals from the magnet. One method of searching for peaks is based on the calculation of variance:

$$\sigma_z(t) = \sum_{i=k-N}^{k} \left(B_z(t_i) - \overline{B}_z\right)^2$$

Where $\overline{B}_z$ is the running average of the last N samples. The calculation of the variance removes the possibility of mistaking a local maximum into a peak from the magnet. The peak of the original curve now becomes a well-define valley or a minimum. To validate that the location is indeed a peak, the measured vertical field can be compared to the estimated earth field. If the difference is large, then it further confirms that a peak has just been passed.

The essence of the peak-mapping methods is to look for a peak since the strengths are strongest near or at the magnet. Once a peak is detected, one will use the measured fields at that location to identify the distance to the marker. The transformation of the measured signals to the distance to the marker is based on a one-to-one mapping relationship.

Figure 11 shows contour maps of the measured field strengths at three different heights. The data points are produced with the data from Figure 10. Measurements from each height produce a unique oval contour without interfering with each other. These contours constitute a basis for position identification. The lines with labels of S1, S2, and S3 represent expected field values at different distances to the magnetic marker with the distances S1<S2<S3. In implementation, the contours as seen on the graph are tabulated in the signal-processing program. A pair of measured lateral and vertical field values near the detected peak can be compared to the tables and the position of the detected peak to the marker is estimated.

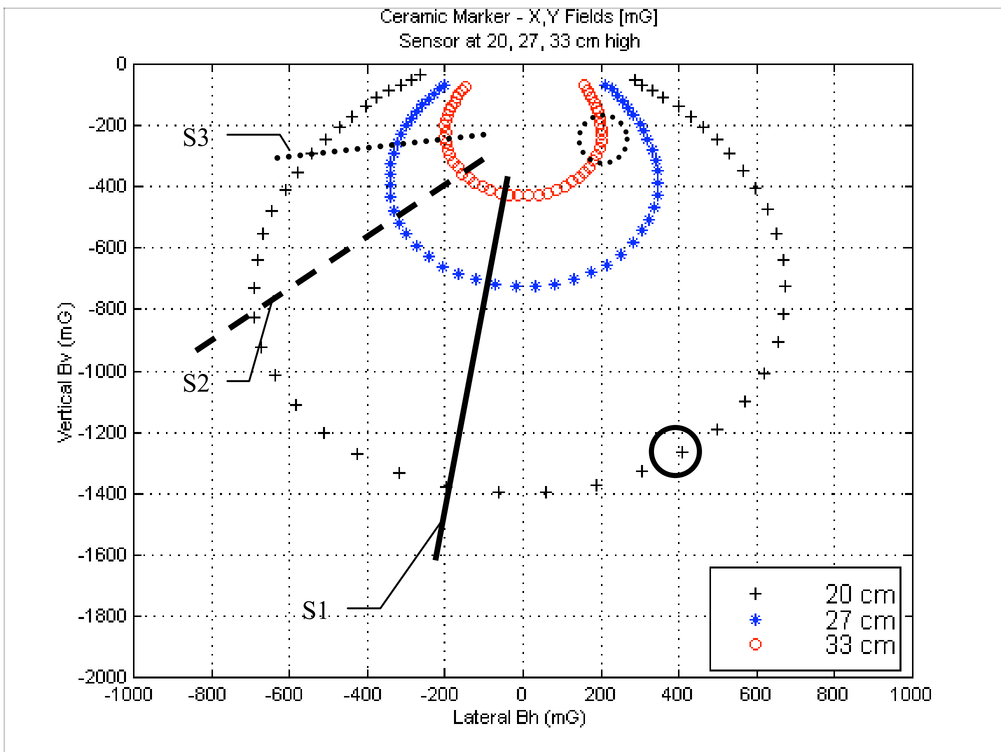

Figure 11. Contour Maps of Lateral and Vertical Magnetic Fields with Data in Figure 11

As can be seen from contour maps, the further away from the marker, the denser the data points are. Therefore, the accuracy of this approach deteriorates when the sensor is distant from the magnet. The robustness of the algorithms, when subject to measurement errors, can be determined by creating an error zone around each point on the contour, such as the two circles in the graph. When the measurement location is close to the marker, as indicated by the solid circle, errors in the lateral or vertical components lead to smaller deviations in estimated distance or height. A similar range of measurement errors at a farther location, as shown by the dott+ed circle, will result in much larger errors in position estimation.

4.2 Differential Peak Mapping [8]

A different approach was suggested to cancel the background noise by assuming that the ambient fields are approximately uniform in a small region, thus the measured fields at two close points can be expressed as:

$$B^{left}(t_k) = B^{left}_{Marker} + B_{Earth} + B^{Left}_{Local}$$
$$B^{rightt}(t_k) = B^{rightt}_{Marker} + B_{Earth} + B^{rightt}_{Local}$$

The earth field is typically much greater than the local disturbances. Therefore, if a differential is taken for the two observation points:

$$\Delta B\ (t_k) = B^{rightt}(t_k) - B^{leftt}(t_k) \approx B^{rightt}_{Marker} - B^{leftt}_{Markerl}$$

The disturbance is directly removed. The approach saves the computation for estimating the disturbances.

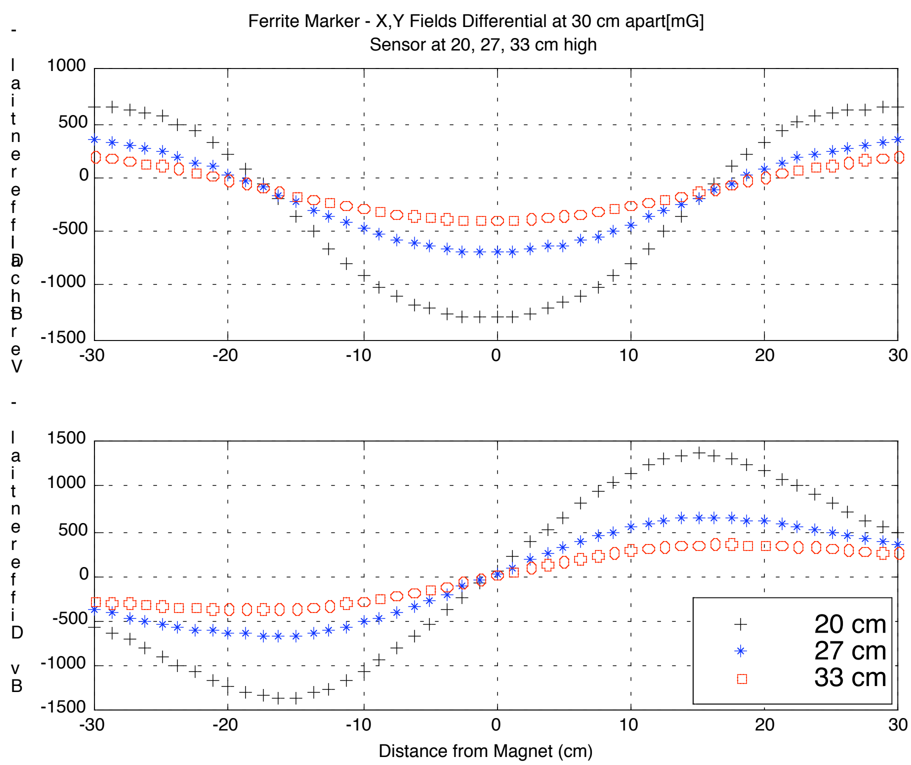

Figure 12. Differentials of Lateral and Vertical Magnetic Fields with Data in Figure 11

The differentials of the lateral and vertical fields in Figure 11 with a 30-cm distance between the measurement points are shown in Figure 12 to demonstrate the differential approach. The lateral differential peaks right at the magnet locations, while the vertical differentials alternate their signs on two sides of the magnet.

A process of correlating the calculated differentials to the measurement location is similar to the exercise that was described in the previous section. The lateral and vertical differentials are plotted versus each other in Figure 13. The lines with labels of S1, S2, and S3 represent expected field values at different distances to the magnetic marker with S1<S2<S3.

A comparison of the two contour maps in Figures 11 and 13 show changes in orientation and magnitude. The points in the contours of Figure 13 are more spread out than those in Figure 12. This means that the same levels of measurement errors will lead to a smaller deviation in position identification in Figure 13. In this regard, the differential approach has a slight advantage over the peak detection method in the previous section.

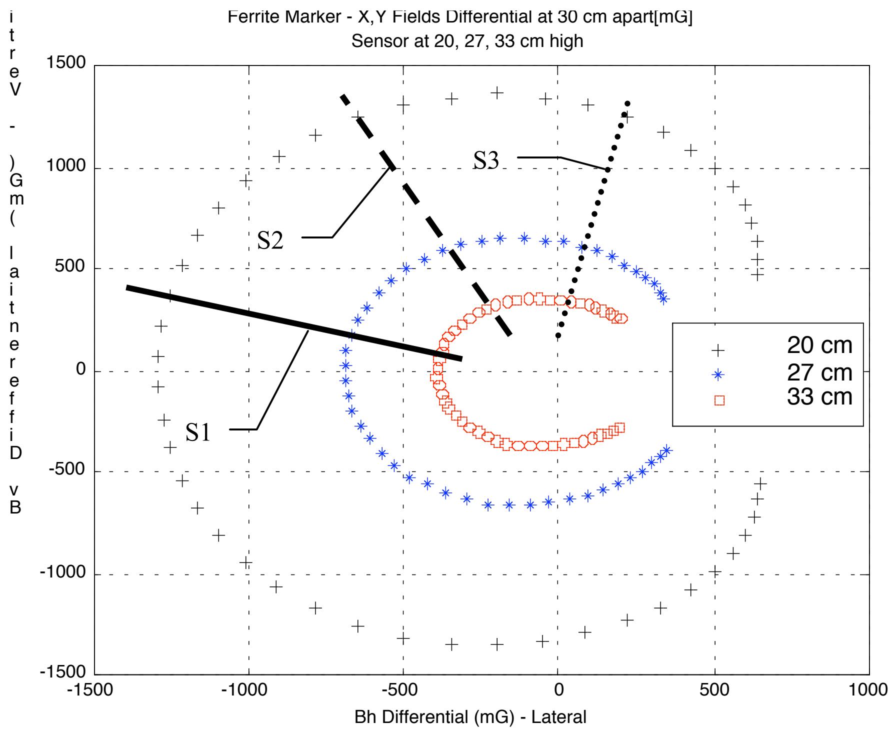

Figure 13. Contour Maps of Lateral and Vertical Differentials with Data in Figure 12

4.3 Vector Ratio Method

An entirely different approach is based on the ratio of field components. Figure 14 shows the ratios of vertical versus lateral field measurements at three different heights from a marker. The curves use the data from Figure 11.

As observed from the graph, the ratios reach large absolute values near the marker and decrease when the measurement point is far from the magnet. It is thus relatively easy in calculation to recognize the approach of a magnet. However, a drawback of this method is that there is a singularity problem in calculating the ratio as the lateral component approaches zero near the magnet. Caution should also be applied in the magnitudes of disturbances, since the deviations in the denominator can have an amplifying effect when the divisor is small. It should be noted that other methods employing ratios of different measured signals are possible. The selection of appropriate vector components depends on the characteristic of the targeted magnetic fields.

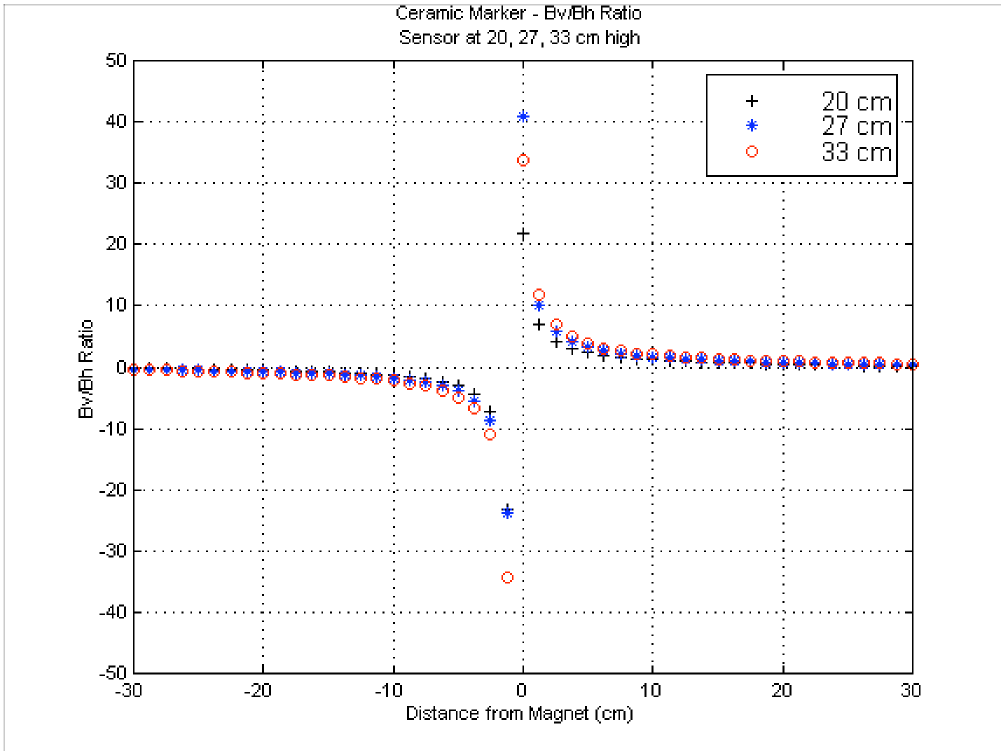

Figure 14. Ratios of Vertical versus Lateral Fields with Data in Figure 11

5.0 Marker Strength Requirements and Installation Guidelines

From the discussions in the previous section, it can be concluded that it is preferable to have strong magnetic fields from the marker so that it can be detected and recognized after the background noise is filtered out. Here is a summary of the basic rules of selecting appropriate magnets for an AVCSS application:

(1) The stronger the magnetic fields of markers, the better as long as the magnetic field measurements at the desired sensor height do not exceed the saturation limits of the selected sensors.

(2) The unit cost of magnetic markers depends on the materials, size, and manufacturers. The cost of magnetic markers, based on experience from most PATH projects, is relatively insignificant when compared to installation and other infrastructure costs. However, the overall system cost can be minimized with a selection of inexpensive magnets for primary installation while special (and often more expensive) units for secondary locations (such as on bridges or specific structures). The current PATH sensing system is able to process signals from different types of magnets even though they may have considerable differences in strength.

(3) The required magnetic strengths of a marker depend on the specific application, and are in particular related to the sensor height. The sensor height in turn is a function of the

available fixture on the subject vehicle and the operating environment. More detailed specifications are given below.

(4) The size of magnets is not critical, strictly speaking, in the implementation of a marker system. However, the preferred shape of markers is cylindrical. A cylindrical shape of the marker allows for easy drilling installation. The preferred size may depend on the specific application and the desired strengths of the magnets at a certain depth beneath the road surface.

(5) Conventionally for past PATH projects, the spacing between markers is 1.0 to 1.2 meters. During the Japan SmartCruise21 Demo, experiments were conducted with spacing of 2, 4, and 6 meters. [5] It was found that performances began to deteriorate with 4-meter spacing in higher-speed and tighter-curve situations. However, for high-precision and slow-speed applications such as precision docking, it will still require a smaller spacing of 1.0 to 1.2 meters. It is conceivable that with careful planning and further validation, spacing can be adjusted up to 2 meters in future applications in highway applications. Since spacing can significantly affect the total number of markers and installation costs, it is desirable to minimize the number of markers. A potential solution in a stretch of roadway may result in the selection of different spacing in steps (such as 1.0, 1.5, and 2.0 meters) to be alternated at different locations to fit the local requirements of roadway configurations and expected maneuvers.

5.1 Desired Properties of Magnetic Markers

The recommendations for magnet properties in the following sections are based on field experiences accumulated over the years of using the magnetic sensing system on several locations, including the test track at Richmond Field Station, I-15 in San Diego and I-80 near the Sierra for snowplow applications.

5.1.1 Magnetic Field Strength

The desirable magnetic field strengths of a marker are given with reference to Figure 15.

(1) The magnetic field measured at Point A shall be greater than 850 Milligauss.
(2) The magnetic field measured at Point B shall be greater than 500 Milligauss.
(3) The height of point A (Y) is 30.48 cm (12 inches) from the top of magnet, and the lateral displacement of point B from A is 1.24 cm (6 inches).

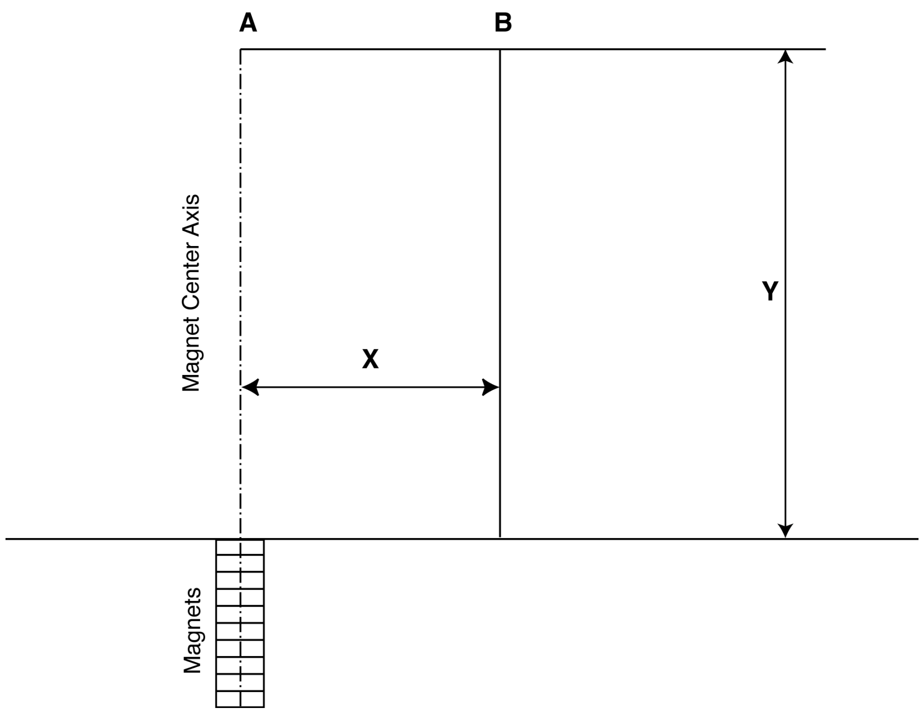

Figure 15. Desirable Magnetic Strength at two Locations from a Marker

5.1.2 Sizes and Shapes

(1) Diameter: Magnets shall be cylindrical with a diameter between 20 mm (0.8 inches) mm and 38 mm (1.25 inches).
(2) Length: Magnets may be stacked together until the field strength requirement is met, to a maximum height of 127 mm (5 inches).

5.1.3 Operating Temperatures

The magnets shall maintain greater than 90% of the magnetic field strength as defined above at temperatures between -35°C and 100°C. Thermally caused changes of magnetization shall be reversible between 100°C and 210°C.

5.1.4 Polarity Identification

All magnets shall be consistently marked at one end to allow for easy identification of the polarity. Identification shall be made by a color, which is easily seen such as neon green, orange or yellow.

5.2 Requirements in Installation and Placement

5.2.1 Lateral Position Accuracy

There are two types of lateral (perpendicular to centerline) accuracy required for magnet placement: position accuracy and smoothness accuracy. Lateral position accuracy specifies the tolerance of the magnet location relative to the reference line. Lateral position tolerance is ±15 mm. Smoothness accuracy specifies the tolerance of a series of magnet locations relative to adjacent magnets. The following requirements are given with reference to Figure 16:

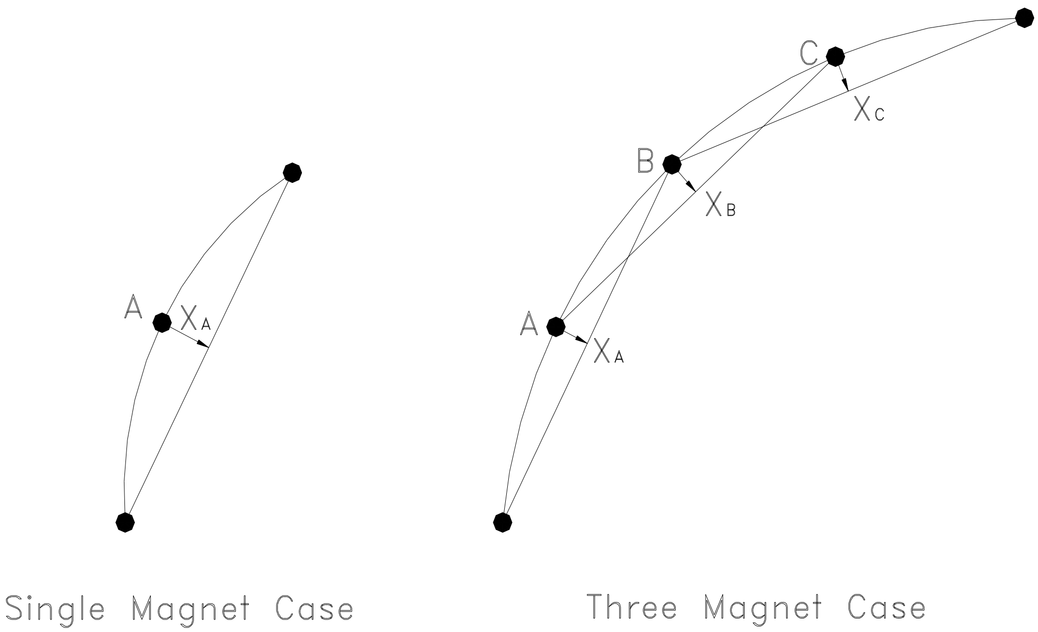

Figure 16 Marker Lateral Accuracy and Smoothness Requirements

For a single magnet
$|X_A| \le 15$ mm

For a series of magnets (3 subject magnets A, B, and C, plus two adjacent magnets)
$|X_A|+|X_B|+|X_C| \le 30$ mm

Smoothness accuracy shall be determined by visual inspection of the hole location marks to see if they form a smooth line or curve. If there are questionable magnet location marks the following procedure shall be used:

1. For a single questionable magnet location $|X_A| \le 15$ mm.
2. For multiple magnet locations (a sequence of 5 magnets in Figure 16):
   A). Measure the offset from the chord between three adjacent magnets (X_A, X_B, X_C)
   B). The sum of the offsets should be less than 30 mm
   $|X_A|+|X_B|+|X_C| \le 30$ mm
   C). Re-mark locations that exceed required smoothness accuracy

5.2.2 Longitudinal Position Accuracy

Magnets shall be placed to within ±100 mm longitudinally (parallel to centerline) of the designated location.

5.2.3 Vertical Position Accuracy

The top of the magnet stack shall be flush or less than 10 mm below the surface of the processed subgrade.

5.2.4 Drill Hole Sizes
Holes drilled or punched into the processed sub-grade shall be perpendicular to the surface and shall be sized to permit snug installation of the stacked magnets. The diameter of the hole shall be less than diameter of the magnet plus H/12, where H is the height of the stacked magnets. All residues shall be removed from the surface prior to paving.

5.4 Cost Estimator Model

The overall cost of a complete system shall at least include the marker materials, installation, vehicle instrumentation, and labor. The following spreadsheet incorporates some of these considerations and shows how the system cost over a number of years can be estimated. For a complete cost model, other related fixed investments and variable costs should also be included. The numbers in the table are only given for illustrations, and the actual numbers may vary. For example, the installation cost for 1609 meters (1 mile) was estimated to be $10,000 in the table below.

Cost Model Spreadsheet for Magnetic Marker Systems

Discount Rate: 6 (%)
* discount rate is the equivalent interest to calculate cost variation year over year

Calculation for number of magnets

Road Length		Spacing btw Magnet		Number of magnets needed
1609	(Enter meters)	1.20	(Enter meters)	1341

Calculation for magnet costs

$1.00	(Enter price per marker)	Total	$1,341.00

System Deployment Cost Calculation

Year	Fixed Cost			Vehicle Cost		Others	Year Total	Acc. Total
	Materials	Installation	Other	No. Veh	Unit Cost			
1	1341	10000		1	5000		$16,341.00	$16,341.00
2				1	5000		$5,000.00	$22,321.46
3				1	5000		$5,000.00	$28,660.75
4				2	2000		$4,000.00	$34,380.39
5				2	2000		$4,000.00	$40,443.22
6				2	2000		$4,000.00	$46,869.81
7				3	1000		$3,000.00	$52,682.00
8				3	1000		$3,000.00	$58,842.92
9				4	500		$2,000.00	$64,373.49
10				4	500		$2,000.00	$70,235.90

Table 1. An Exemplar Cost Estimation Model

6.0 Formulation of Magnetic Sensing Problem and Its Optimization

In this section, we will formulate the sensing problems and discuss the general approaches for optimizing a magnetic sensing system.

6.1 Magnetic Fields

There exists a magnetic field as detected in a three-dimensional space. At each point in space and at a certain time, a vector, (B_x, B_y, B_z), represents the magnetic flux. The vector forms of the field magnitudes from all the points in the space constitute a picture of magnetic flux.

In a magnetic sensing system, a pre-known pattern of magnetic fields is inserted into the existing background field. For example, a discrete sequence of magnetic markers embedded in a stretch of roadway is arranged such that a marker field can be recognized at a pre-known spacing. There can be many forms of magnetic material configurations in various shapes and sizes. The magnetic field created by the insertion of the magnetic materials can be experimentally measured or mathematically modeled.

Besides the inserted magnets, the magnetic fluxes may come from other sources, including the earth field, and interference caused by scattered debris on highways. Another source of noise may come from electro-magnetic effects due to equipment placed near the measurement spot. The remaining form of noise is random, which may include those sources that cannot be identified in the other categories.

In summary, the measured magnetic field of interest comes from several sources; some of which can be quantified in advance while others may appear in irregular or random patterns.

$$B_B(x,y,z,t) = B_{MM}(x,y,z,t) + B_E(x,y,z,t) + N_{EO}(x,y,z,t) + N_{OP}(x,y,z,t) + N_R(x,y,z,t)$$

Where the components of the magnetic field come from:
B_{MM}: Magnetic markers
B_E: Earth
N_{EO}: Noise from external objects
N_{OP}: Noise from equipment operation
N_R: Random noise

Some components of the expected fields are slowly varying or non-variant over time. However, for the intended applications when vehicles move along an instrumented path, the time sequences of measurements vary drastically from one time to another due to the different offsets or orientation of the vehicle trajectories.

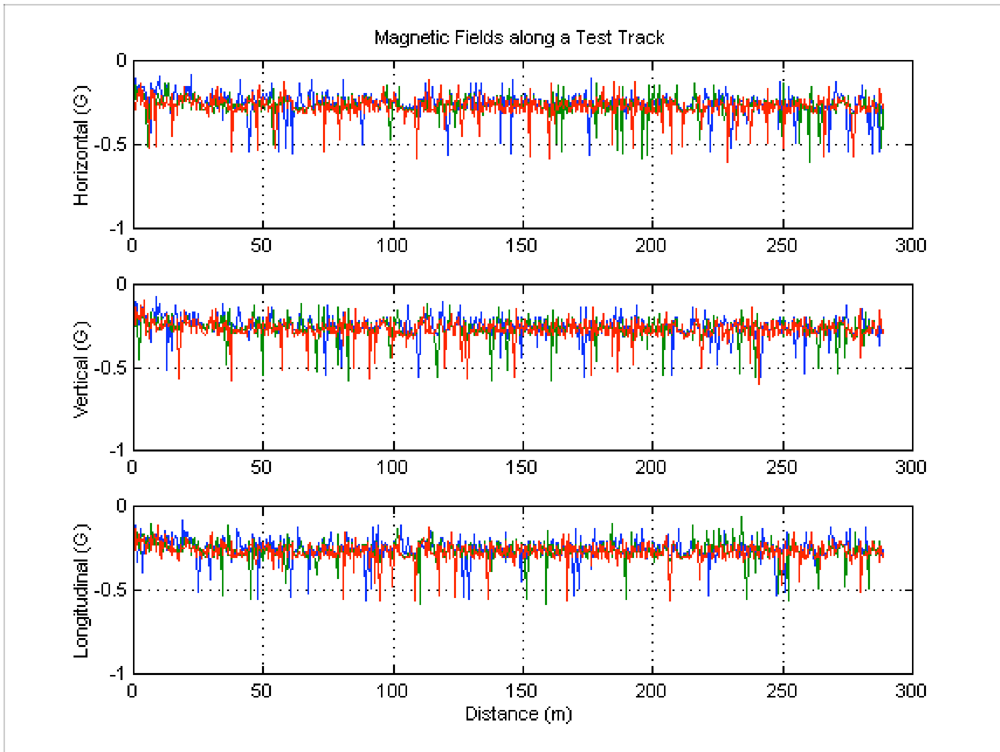

Figure 17. A Set of Test Track Data with Installed Magnetic Markers

6.2 Sensing Problem

Given the measurement of magnetic fields as the sensing device moves in a trajectory across the three-dimensional space, the existence of inserted magnetic materials is to be recognized and the measured signals are to be correlated to the position relative to inserted magnets. The field data collected by a sensor contains a time history of signals sampled along the trajectory of the sensing device, $B_{SD}(t) = B(x_{SD}(t), y_{SD}(t), z_{SD}(t))$. Figure 17 shows a sampling of acquired data points along a test track at the PATH Richmond Field Station facility. The three traces of data in the graph come from three separate sensors mounted 30 cm apart under the rear bumper of a test vehicle, approximately 25 cm (10 inches) above the ground level. For ground vehicle guidance and control applications, essentially the task is to process $B_{SD}(t)$ to generate an output of a sequence of position indicators relative to the inserted magnetic markers.

If the sensing approach depends on data collected from more than one sensing devices, then signal processing involves data sets from multiple sensors simultaneously, $\square_{i} B_{SDi}(t)$. The use of multiple sensors provides potential benefits. One is to remove ambient fields by mutual subtraction, if the two measurements contain the same levels of background measurements. The other is to rely on the differential of the two measurements as the basis of signal processing as suggested in Section 4.2. Another approach of utilizing multiple sensors is to allow individual processing at each sensor but to place different weights on two adjacent sensors for a combined estimate.

6.3 Design Preferences and Constraints

Since the ground (infrastructure) and the moving (vehicle) portions of the magnetic sensing system should be independent for an ideal and a flexible system, it is reasonable to examine the design objectives and constraints in each category separately.

From the infrastructure view, there are several desirable features:
(1) The ground materials should provide the maximum field strength. A strong field from the inserted materials is a pre-requisite for a high signal to noise ratio, which in turn enhances the probability to filter out the noise and to recognize the meaningful signals.
(2) The shape and size of the magnets should be selected to allow an easy and a reliable installation process. In particular, when systems are considered for large-scale implementation, the size and shape of magnets should be selected to suit an automatic installation procedure and to achieve maximum durability.
(3) The infrastructure should allow for the embedding of information to enrich the usefulness of magnetic materials. A significant feature of magnetic marker systems is the capability of the system to embed a coding scheme into a sequence of markers on a roadway. Each marker is represented by its polarity, thus a sequence of varying polarity chosen for markers form a specific code to denote a certain geographical feature, such as road curvature, or to identify a specific location, such as a milepost.
(4) With a discrete system, such as magnetic markers, a system can generally benefit from compact and tight spacing, which provides frequent position update. However, the ground magnets should be arranged at the maximum acceptable spacing for cost reduction.

From the vehicle point of view, the key constraints are:
(1) The sensor height should not interfere with operations in anticipated conditions. This presents a conflicting limitation since an elevated position of the sensors will see reduced strengths of the magnetic fields from the magnet.
(2) The placement of sensors should be arranged to cover the required range. However, the total number of sensors should be kept low for cost considerations. The effective range of each sensor is affected by the sensor height.
(3) The measurements from all sensors should be adequate collectively to reflect the orientation and position of the vehicle. For example, with sensors at the front and rear ends of a vehicle, the orientation of the vehicle relative to the line of magnet installation can be calculated. PATH researchers have utilized such a configuration to form a concept of virtual forward-looking by projecting a mirror image of the rear sensor to a point leading the vehicle.

6.4 A Perspective of Sensing System Optimization

When implementing a magnetic system, one must first consider the essential requirements of the targeted applications. For example, a precision-docking operation will have different requirements on accuracy and range from a lane-departure warning system. The basic guidelines or requirements for advanced vehicle control and safety systems (AVCSS) include desired accuracy, desired range, desired coding capability, desired update rate for control purposes, and reliability or failure rates. There are several levels of requirements for reliability definitions.

Among them are the failure to read one single magnet, failure to interpret a code, failure of single sensor, failure to generate a proper output, and failure to perform at the system level.

In searching for an optimal configuration of a magnetic system, there are separate issues to consider in selecting or constructing components or sub-systems. In Table 2, the objectives, limitations, and design issues for the major sub-systems are outlined.

Sub-System or Components	Objectives, Limitations, and Issues
Magnet	• Size • Shape • Material • Uniformity among units • Cost – material + installation • Distribution of magnetic flux near magnets
Sensing algorithms	• Minimum levels of signal strengths • Tolerance of measurement error in sensing algorithm • Variation of sensing accuracy versus heights • Variation of sensing range versus heights • Filtering schemes • Sampling Rate • Update rate
Sensor assembly	• Height from ground or magnet • Number of sensors • Multiple sensor design with individual and combined signal processing • Mounting location on vehicle • Electromagnetic interference from vehicle and on-board equipment • Wiring harness, power supply, and networking • Cost
Infrastructure	• Particular features of ambient fields; location specific disturbances • Coding requirements • Roadway geometry • Potential defects or variations in installation • Durability of Pavement and magnet • Survey accuracy requirements • Installation Methods • Cost
Operation	• Variation of measurement heights due to vehicle motions (roadway roughness, potential vertical motions and potential pitching motions) • Repeatability of maneuvers • Operational requirements, such as hours and frequency of use

Table 2. Design Objectives and Constraints of Sub-Systems in a Magnetic Sensing System

In order to establish a flexible optimization procedure for a magnetic system, it is suggested that evaluation models for each sub-system should be constructed first. The models will allow the inputs of design parameters with defined constraints and produce respective outputs. For example, the magnet evaluation model will generate outputs of field distribution and unit cost based on the inputs of size, shape, and materials or manufacturers' information. The evaluation model for sensing algorithms will take inputs of sensor placement strategy, operating heights, magnet field distribution, sampled background noise, then produce a sequence of position indicator relative to installed magnets and coding interpretation if codes exist. An algorithm described in Section 4.1 is the preferred method as deployed by PATH in several applications. The evaluation models of sub-systems will interact with each other in an iterative process until an optimal or a compromised set of components is selected. Once an acceptable system is assembled, the cost figures from all the sub-systems will be fed into an overall cost model that takes into account magnets, sensor assembly, installation, maintenance, replacement cycle, and expected service life cycles.

7.0 CONCLUSION

In this report, we discussed the sensing techniques and implementation issues of magnetic sensing as a position reference system. The field patterns of sample magnetic markers were first measured to illustrate the basic characteristics of such systems. Several sensing approaches were explained and compared with regard to their functioning principles and sensitivity to measurement variations. Three particular algorithms were discussed with illustrations of respective mapping methods. Robustness and sensitivity of the sensing methods, when subject to signal noises and parameter variations, are desirable features.

A framework for dealing with technical limitations and objectives is outlined. The constraints and preferences of sub-systems and the corresponding issues are listed for further evaluation of described sensing systems. The optimization of such systems can only be accomplished by building the appropriate evaluation models for each component and the overall system. With the increasing deployment of magnetic sensing systems for position reference, these subjects deserve elaborated studies and thorough analysis.

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