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An Indoor Absolute Positioning System with No Line of Sight Restrictions and Building-Wide Coverage

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Abstract

Accurate sensing of vehicle position and attitude is required in many mobile robot applications, but is a very challenging problem in real office building or warehouse environments. Many existing indoor positioning systems are limited in workspace and robustness because they require clear lines of sight, have insufficient coverage area, or do not provide absolute measurements.

This work presents a new absolute position and attitude sensing system with no line of sight restrictions and an operating area that can span an entire office building or warehouse. The system uses beacons fixed at known locations throughout a building to create dipole magnetic fields. All of the beacons produce fields at all times, and a code division multiple access (CDMA) method is presented to distinguish between the fields produced by the individual beacons. This method provides advantages over existing magnetic field techniques in coverage volume, accuracy, and resistance to distortion. Initial experimental results demonstrate centimeter-level positioning accuracy.

1 Introduction

Mobile robots are providing service in a growing array of indoor applications. Their use ranges from the redundant (e.g. warehouse automation, inspection tasks [22], floor sweepers [20]) to the dangerous (e.g. mining [19], reactor cleanup [17]). They can cut the costs of routine operations (e.g. delivery in manufacturing plants, office buildings, or hospitals [8,18]), or provide round-the-clock service for the disabled [25]. Other applications include security [5] and telepresence [23].

Numerous sensing technologies have been used to provide the positioning information required in these applications [6]. But each of these technologies typically places particular constraints on the operating environment. For example, overhead cameras have been used to track infrared LEDs on mobile robots. The result is millimeter-level position accuracy, but clear lines of sight must be maintained between cameras and robots. On-board vision, ultrasonic and indoor pseudolite-based differential carrier phase GPS systems [13] also require unobstructed lines of sight. Systems based on inertial sensors or wheel encoders avoid line of sight issues, but their measurements are not absolute and are subject to error accumulation. Hybrid systems are available which use absolute sensors coupled with inertial sensors [10]. This provides limited duration coverage in areas the absolute sensor does not reach by itself.

Systems based on magnetic fields offer an important alternative by providing absolute position and attitude information with no line of sight restrictions. Currently available systems, however, are limited in range, providing coverage areas insufficient for a building-wide application [2,16]. Furthermore, the two technologies currently used, based on time division and frequency division methods, each have their own strengths and limitations. To provide a better context for the work in this paper, these two approaches are discussed further in Section 3.

This paper presents an absolute position and attitude sensing system with no line of sight restrictions and an operating area that can span an entire office building or warehouse. The system is capable of providing 10 Hz position estimates, and the vector nature of the measurements allows attitude determination with a single small sensor. Such a system not only provides 'go-anywhere' freedom to mobile robots, but has application to other areas such as object and personnel tracking, augmented reality, and motion capture.

The system uses beacons fixed in known locations throughout a building to create dipole magnetic fields. All beacons produce magnetic fields at all times, but the current through each of the beacons changes polarity according to a unique pseudorandom code. A mobile sensor unit samples the local magnetic field and uses correlation to determine the portion of total field strength due to each individual beacon within range. The measured field strengths from several beacons, along with the known beacon locations, allow determination of mobile sensor position and attitude.

The code division multiple access (CDMA) method presented here combines the advantages of existing magnetic field positioning systems, allowing numerous

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beacons to be active at the same time while retaining the benefits of sampling the magnetic field as it approaches a steady state value. The CDMA method offers intrinsic rejection of common forms of noise. Furthermore, CDMA provides a natural method to greatly increase the number of beacons in the system, resulting in increased coverage volume, accuracy, and resistance to distortion.

Background on magnetic fields, and on the two commercially available technologies, is provided in the next two sections. The use of multiple beacons through CDMA techniques is described in Section 4, followed by the algorithms used to estimate position given magnetic field strengths from several beacons. Finally, experimental hardware and results are presented.

2 Background

A magnetic field is created when electrical current flows through a wire. A constant current flowing through a circular loop of wire (Figure 1) produces a constant magnetic field called a dipole field. At a particular point, the vector magnetic field strength is given by (in spherical coordinates) [9]

$$\overline{B} = \frac{\mu_0 N I a}{4\pi r^3} \quad (2\cos(\theta)\,\hat{r} + \sin(\theta)\,\hat{\theta}) \qquad (2.1)$$

where $\mu_0 = 4\pi * 10^{-3}$ G m/A (permeability of free space)
N = number of turns of wire
I = current
θ = elevation angle
r = distance from center of loop
R = radius of loop
a = area of loop = πR^2

This theoretical result is valid for points that are at a distance of several times the loop radius, i.e.:

$$|r| >> R$$

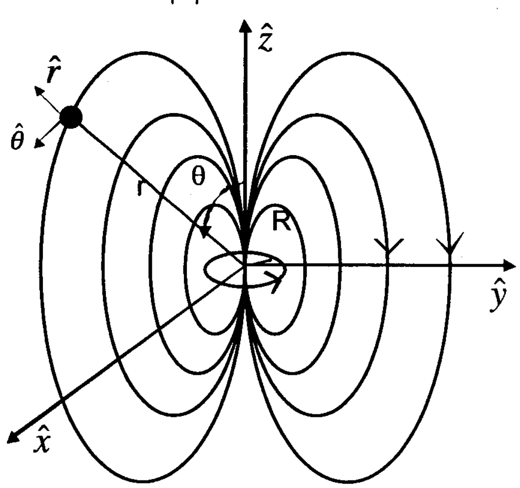

Figure 1. Dipole magnetic field created by current flowing through a coil of wire.

This theoretical expression also assumes the total cross-sectional area of the wire itself is small compared to the loop radius R. Magnetic fields are measured in Gauss (G) or Tesla (T), with $1T=10^4G$.

Magnetic fields obey superposition and therefore simply add as vectors. Thus, a magnetic field sensor at some point in space measures the total magnetic field in each of three orthogonal axes. That total magnetic field could be the vector sum of several dipole magnetic fields created by coils of wire, plus the earth's magnetic field, plus any additional sources such as permanent magnets or 60 Hz power lines.

3 Commercially Available Magnetic Field Positioning Systems

Commercially available technologies typically use circular coils to create dipole magnetic fields. Each 'transmitter' unit contains 3 coils oriented in orthogonal directions. If the vector field strength produced from each individual coil can be determined (3 components from each of 3 coils = 9 measurements), the position and attitude of the sensor can be estimated. Since magnetic fields superimpose, however, the process is not as simple as turning on all three dipoles and recording the field strength along each axis. This would only result in the total magnetic field being measured in each vector direction (only 3 measurements). Thus a more sophisticated method is required to distinguish the magnetic fields produced by each individual coil.

There are currently two commercially available technologies that use these dipole magnetic fields. One technology, from Polhemus, uses low frequency AC magnetic fields [16]. Each coil produces a field varying at a particular frequency. A mobile sensor unit takes several measurements, and the field strength from each dipole can be resolved with frequency filtering. Thus, this system is using frequency division multiple access (FDMA) methods. The longest range system offers approximately a 50' x 50' coverage area.

A second available technology, termed 'pulsed DC', is used in several systems from Ascension Technologies Corporation [2]. This technology uses time division multiple access (TDMA) to distinguish the field created by each dipole. Using this technique, each coil turns on and off in sequence, so no two are operating at the same time [4]. The field from each coil is allowed to approach a steady state value, and then sensor readings are taken. This system has a 40' x 20' coverage area with a maximum of two transmitter units.

One advantage of the FDMA approach is that multiple beacons can produce magnetic fields at the same time. This would be an important feature for a system, such as that described in this paper, which allows hundreds of beacons to be located throughout a building. If only one beacon could be active at a time in any given area (as in TDMA), then the sensor would spend most of its time measuring only noise as the system cycles through the far away beacons. Also, for a given sensor rate, the time slot during which each of the beacons produces its magnetic field gets shorter as the number of transmitters increases. Because of finite rise-time limitations (due to coil inductance), the magnetic fields will be smaller, affecting signal to noise ratios and accuracy. Thus, FDMA is more readily scalable to large numbers of beacons.

A second advantage of FDMA is that it naturally rejects large steady-state biases, such as from the earth's magnetic field or a permanent magnet. Commonly occurring 60 Hz magnetic field noise is also filtered out.

However, several experimental studies have found the TDMA method to suffer from significantly less distortion in the proximity of non-ferrous metals [1,3,4]. This is because eddy currents are created in conductors by time-varying magnetic fields. These currents create magnetic fields of their own, distorting the pure dipole field expected. With the AC system, these eddy currents are always present, but the pulsed DC method allows fields to approach a steady state value before a measurement is taken. This allows the eddy fields to damp out. This resistance to distortion would also be an important feature for a robot positioning system operating in a real warehouse environment.

4 Multiple Beacons Through the Application of CDMA

The goal of this research is to develop an absolute positioning system with no line-of-sight restrictions that can cover a building-sized volume. This was achieved through the application of CDMA techniques to a magnetic field positioning system. The CDMA approach presented here combines the advantages of the FDMA and TDMA magnetic field technologies, allowing numerous beacons to be active at the same time while retaining the benefits of sampling the magnetic field as it approaches a steady state value. The CDMA method offers intrinsic rejection of common forms of noise. Furthermore, CDMA provides a natural method to greatly increase the number of beacons in the system, resulting in increased coverage volume, accuracy, and resistance to distortion.

To achieve the large coverage area, multiple beacons are installed in known locations throughout the building. The beacons can be laid out in a lattice, with 4 to 5 m between adjacent beacons. This would allow beacons to be installed in unobtrusive locations such as a crawlspace between a ceiling and the floor of the next higher level. The distance between beacons can be increased or decreased, and numerous tradeoffs can be made among accuracy, beacon separation distance, beacon power consumption, code length, and sensor output rate. Hundreds or thousands of beacons can be used, providing a large volume of continuous coverage.

Each beacon, as defined in this paper, consists of a coil of wire and power electronics to create a dipole magnetic field similar to that shown in Figure 1. Electrical current can be driven through the coil in either direction. Thus the magnetic field strength vector at any point in Figure 1 can be aligned in either one of two directions, depending on the direction of current flow.

All beacons produce magnetic fields at all times. Each beacon, however, periodically changes the polarity of the current through its coil. The changes occur according to a 'pseudorandom code', a special sequence of 1's and -1's. Each beacon is assigned its own code, and the code repeats when its end is reached. The pseudorandom codes are chosen from families of codes with good orthogonality properties. That is, the peak cross-correlation value of any two of these special vectors is small (compared to the peak autocorrelation of either vector). Each element of the sequence is called a 'chip' in CDMA terms. The codes used in the experimental section of this paper were chosen to be Gold codes of length 1023 chips. The beacons are synchronized so that all code sequences start and recycle at the same times. The first 20 chips in 3 Gold code sequences are shown in Figure 2.

The mobile sensing unit samples the magnetic field at its location in each of three directions. This sampling occurs once at the end of each chip period, allowing the magnetic field to approach a steady-state value (ideally to within the quantization noise of the A/D converter on the sensing unit). Thus, this CDMA method is also resistant to distortion in the presence of non-ferromagnetic metals (similar to the TDMA method). Figure 3 illustrates the relation between sensor sample time and the magnetic field produced by one beacon.

The orthogonality of the Gold codes allows the field strength from each individual beacon to be estimated through correlation. An example of this follows, with reference to Figure 2. If beacon 1, using Gold code sequence 1, was the only beacon producing a magnetic field, the sensor would record a magnetic field strength in some axis as shown in Figure 2(a), perhaps with some large offset due to the earth's magnetic field. The magnitude is typical of that found in the experimental section. If beacon 2, with Gold code sequence 2, was the only active beacon, the sensor would record the magnetic field shown in Figure 2(b). The magnitude is smaller because beacon 2 located at a greater distance than beacon 1. Similarly for beacon 3 in Figure 2(c). The sequences in this example are portions of 1023-chip Gold codes.

If, however, all three beacons are active at the same time, the mobile sensor records the sum field, a portion of which is shown in Figure 2(d). Measurements are made at the end of each chip interval, so, for this example, the

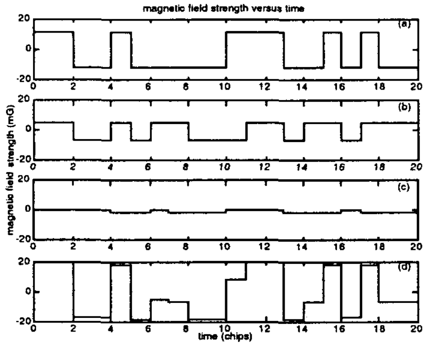

Figure 2. First 20 measurements taken with (a) only beacon 1 active (magnitude is 12), (b) only beacon 2 active (magnitude is 6), and (c) only beacon 3 active (magnitude is 1). Graph (d) contains the measurements taken with all 3 beacons active

measurements in Fig. 2(d) • beacon 1 Gold code	11.99
measurements in Fig. 2(d) • beacon 2 Gold code	5.99
measurements in Fig. 2(d) • beacon 3 Gold code	0.98

Table 1. Inner product of measurements in Figure 2 (d) and the Gold codes of beacons 1, 2, and 3, respectively.

measurement vector has length 1023. The first element of the measurement vector must be taken during the time the beacons are producing magnetic fields according to the first chip in their Gold code sequences.

Correlation is used to distinguish the field produced by the *i*th beacon. First, the bias is subtracted from the measurement vector to eliminate any steady state noise such as the earth's magnetic field. Then, the inner product is taken between the vector of measurements and the vector containing the Gold code for the *i*th beacon (a vector of 1's and -1's). The inner product is normalized by the number of chips in the Gold code (1023). The result B_i is an estimate of the field strength from the *i*th beacon. Thus

$$B_i = C_i \bullet M/1023 \qquad (4.1)$$

where C_i = vector containing Gold code *i*
M = measurement vector
B_i = estimate of field strength from beacon *i*

The results in this example are shown in Table 1. The correlation procedure is effective at attenuating interfering signals that do not have the shape of the desired Gold code, such as 60 Hz noise [14].

After the values of B_i have been obtained, a correction step can be performed to approximately account for the small cross-correlation between Gold codes, since they are not perfectly orthogonal. However, the experimental results showed that this term had negligible effect on position or orientation accuracy.

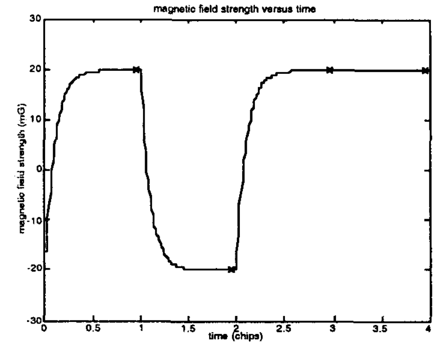

Figure 3. Magnetic field created by one beacon over four chip periods. The sensor samples the field at the ('x') marks.

The sensor unit must be synchronized with the beacon codes to ensure that the first element of the measurement vector (equation 4.1) was captured at the time the beacons were producing magnetic fields according to the first chip in their Gold codes. Synchronization is also required to ensure measurements are taken at the end of each chip period (as in Figure 3). This timing information can be sent through a communication link between a base station and the sensor unit. In many mobile robot applications, this communication link to the robot already exists. If 10 Hz position estimates are desired and length 1023 chip Gold codes are used, one chip period will be 98 μs. Thus, the timing information requires accuracy only on the order of 1 to 10 μs.

A second method to synchronize the sensor unit with the beacons does not require a communication link. The mobile sensor unit dedicates one magnetic field sensor to taking fast (1 MHz) samples of the magnetic field. A filter is then applied to this data to identify changes in the local magnetic field which occur periodically at the known beacon chip rate. This provides an estimate of the start time of each chip, but not the start time of the code sequence. To determine the start time of the code sequence, the cross-correlation between the measurement vector and the code vector is calculated. The location of the peak of the cross-correlation vector gives the time offset between measurements and the start of the code sequence. Gold codes are well suited to this method because of their autocorrelation properties [14].

Note that any binary orthogonal coding sequence could be used for this application. The family of Gold codes with 1023 chip sequences, chosen for this initial experiment, has 1025 members, so 1025 beacons could be used in a system with no duplication issues. Longer codes could be used for an even greater number of unduplicated beacons in a system, but there are, of course, resulting tradeoffs. Longer codes may increase the time between position estimates, force the use of smaller magnetic fields, or increase the beacon power consumption.

The increased number of beacons enables not only a much larger coverage area, but also an increase in the number of measurements and the opportunity for better measurement geometry (lower geometric dilution of precision). Given all other conditions the same, a larger number of beacons has advantages of higher accuracy, greater mitigation of distortions, and redundancy to beacon failures.

5 Algorithms

The estimates B_i (4.1) are used to determine position and orientation of the sensor. If the 8 closest beacons are used (as in the experimental results), there are 8 field strength measurements in each of 3 sensor axes, for a total of 24 measurements. For the case where all 8 beacons are oriented in the +z direction, the measurements are related to the position of the sensor by the following 24 equations

$$\begin{aligned} B_{ix} &= 3k(x-x_i)(z-z_i)/r_i^5 \\ B_{iy} &= 3k(y-y_i)(z-z_i)/r_i^5 \\ B_{iz} &= k(2(z-z_i)^2-(x-x_i)^2-(y-y_i)^2)/r_i^5 \end{aligned} \qquad (5.1)$$

where $i = 1...8$ (beacon index)
$r_i = ((x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2)^{1/2}$
x, y, z = sensor position
x_i, y_i, z_i = position of beacon i
B_{ix}, B_{iy}, B_{iz} = estimate of magnetic field created by beacon i (in x-, y-, or z- direction)
$k = \mu_0 NIa/4\pi$

Given the 24 measurements of magnetic field components and the beacon locations, it may be possible to solve these equations for the sensor location. With no *a priori* knowledge of position, the procedure would be to arbitrarily pick a reasonable initial position, linearize about that point, and solve for the sensor position using weighted least squares. The process would iterate until the solution converges. However, due to the nonlinearity of these equations, if no *a priori* information is known about the position, this algorithm does not converge when applied to these nonlinear measurement equations.

Furthermore, note that these equations (5.1) assume prior knowledge of orientation, so that the measured field strength vector can be written in a building-fixed (x, y, z) coordinate frame. If attitude information is not known, further equations must be combined to relate the building-fixed coordinate frame to the (u, v, w) sensor coordinate frame. One method is to use a direction cosine matrix

$$\begin{bmatrix} B_{iu} \\ B_{iv} \\ B_{iw} \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & C_{23} \\ C_{31} & C_{32} & C_{33} \end{bmatrix} \begin{bmatrix} B_{ix} \\ B_{iy} \\ B_{iz} \end{bmatrix} \qquad (5.2)$$

A step towards a potential solution is to combine the component position equations (5.1) to form 8 magnitude equations (again for the example of 8 beacons oriented in the +z direction)

$$|B_i| = k(3(z-z_i)^2 + r_i^2)^{1/2} \;/\; r_i^4 \qquad (5.3)$$

These equations can also be written in spherical coordinate form, resulting in further simplification

$$|B_i| = k(1+3\cos^2\theta_i)^{1/2} \;/\; r_i^3 \qquad (5.4)$$

where θ_i is the angle between the axis of the *i*th beacon and the vector from the *i*th beacon to the sensor, as shown in Figure 1. Attitude information is not needed, and the system of equations has been reduced to 8 equations (for 8 beacons) and 3 unknowns (x, y, z). However, both experiment and simulation show an iterated, linearized solution based on this system of equations again does not converge without *a priori* knowledge of position.

There is a simplification, however, that overcomes the convergence problem. Notice that the $(1 + 3\cos^2\theta)^{1/2}$ term in equation (5.4) is always between 1 and 2, and that the $1/r^3$ term dominates the equation. If the $(1 + 3\cos^2\theta)^{1/2}$ term is simply approximated as 1.5, then the equations are of the form

$$|B_i| \approx 1.5k \;/\; r_i^3 \qquad (5.5)$$

These equations can be easily transformed to be of the same form as the GPS pseudorange equations [15] (without the bias terms), and these equations are well known to have very good convergence properties [15]. In fact, an algorithm based on equation (5.5) will converge without *a priori* knowledge of position, but not to the same solution as equation (5.4) due to the simplification step. However, simulation and experiment shows that, because the simplification does not affect the dominant $1/r^3$ term, the algorithm based on equation (5.5) typically converges to a solution within 20 cm of the actual sensor position. Thus, equation (5.5) can be used to estimate a rough position solution without prior knowledge of position. This solution then provides an initial estimate for an iterated linearized weighted least squares solution based on the more precise equation (5.4).

Thus, with no prior estimate of position or orientation, the algorithm to estimate position given measurements B_i is as follows:

1) Use approximate equation (5.5) to find an initial estimate,
2) Use the initial estimate from step (1) as the starting point for solving equation (5.4).

Notice that only magnitude equations are used in this algorithm to estimate position - attitude information is not required. Thus the position and attitude problems have been broken down into two steps. This allows simpler and less computationally expensive solutions.

Once an estimate of the position has been obtained, orientation can also be estimated. Using the estimate of position, the magnetic field strength at the sensor location due to the ith beacon, B_i, is calculated from the theoretical equation (2.1), with the result in building-fixed (x, y, z) coordinates. The same vector B_i was also found in sensor coordinates (u, v, w) from the measurements and equation (4.1). Thus, both 3 x 1 vectors in equation (5.2) are known. Equation (5.2) is written for each of the n beacons closest to the receiver, and the goal is then to solve for the (least squares optimal) rotation matrix (with elements C_{ij}) that relates these two vectors. This rotation matrix describes the attitude of the sensor with respect to the building-fixed coordinate frame.

This problem has a long history and well known algorithms for the solution. It was first posed by Wahba [24], motivated by the optimal estimation of the attitude of a satellite. A solution appeared in [7], and a bibliography of numerous improvements and modifications are referenced in [12]. For simplicity, the singular value decomposition method, as described in [12], was used for this experimental work. Examples of computationally faster methods appear in [11,21].

The elements of the direction cosine matrix, once estimated, contain all of the information needed to convert to other attitude representations, such as Euler angles.

6 Experimental Hardware and Results

Initial experiments have verified the use of the CDMA techniques and algorithms presented in this paper to determine the position of a sensor unit. The experimental platform, shown in Figure 4, consists of eight beacons at the corners of a 2.13 m by 2.13 m by 1.78 m region. Each beacon (Figure 5) is oriented in the upward (+z) direction, and has a coil with 19 turns of wire around a 0.298 m diameter form.

A control unit synchronizes the beacons and is responsible for sending each beacon a unique Gold code. In this initial experiment, a timing signal is also sent to the sensor unit so measurements can be taken at the proper times. This auxiliary timing signal will be eliminated in future versions as timing information can be obtained from a communication link or derived from a fast sampling of the magnetic field, as described in Section 4. Approximately 10 amps of current flows through each beacon coil, creating magnetic fields of 14 mG at 1 m distance. The code rate of this initial experiment is only 50 Hz due to sampling rate limitations of the A/D converter in the sensor unit. Thus, the total time required to take 1023 measurements is over 20 seconds. In future experiments, the code rate will be increased to approximately 10 kHz to obtain position estimates at 10 Hz. In order to achieve the higher code rates, beacons must be constructed with fewer turns of wire to lower their inductance, but this in turn reduces the strength of the magnetic field produced.

The sensor unit uses three orthogonal Honeywell magnetic field sensors based on magnetoresistive technology to make the vector measurements. An A/D converter samples the data, under the control of a small microcontroller. For this initial experiment, the raw A/D output values were sent to a PC for analysis. Future work will integrate a single board computer into the sensor unit. Thus, a future sensor will be a stand alone module that samples the local magnetic field and processes the data to produce position and attitude estimates. If the timing information is derived from a fast sampling of the magnetic field, even a communication link will not be required. The actual magnetic field sensing semiconductors are quite small (all three can fit in 2 cm^3), so the sensor size is determined by the electronics. Because of the vector nature of the measurements, attitude information can be determined from one small unit - no baselines are needed, as with systems based on time-of-flight measurements, such as indoor GPS.

Figure 6 shows a plot of the magnetic field measurements (in one axis) versus time when only one beacon was active. This plot compares the measurements ('x') with the theoretical magnetic field ('o') that should be produced by the beacon with that particular Gold code.

In Figure 7, magnetic field measurements in one axis are shown versus time when all 8 beacons are active. Note the noise-like nature of the sum of the Gold codes, i.e. there is no apparent structure as there was in Figure 6. For

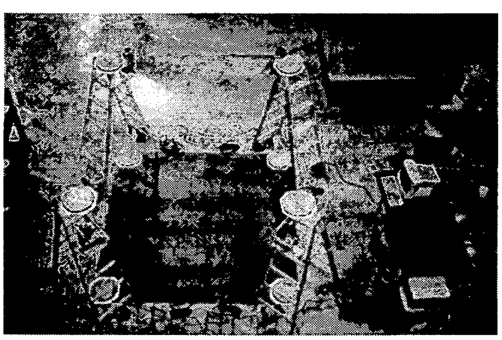

Figure 4. Overhead view of the experiment area.

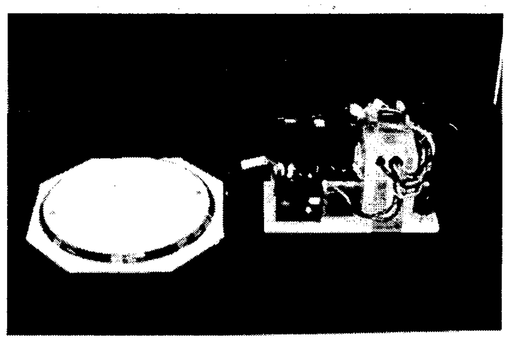

Figure 5. Magnetic field beacon.

comparison, Figure 8 shows the ambient noise in the experiment area when no beacons are active, with the large offset due to the earth's magnetic field subtracted out. Thus, the prototype positioning system has raised the magnetic field noise floor by approximately an order of magnitude. (There are no noticeable side effects of this increase in noise - the fields in this experiment are more than an order of magnitude less than the ambient earth field). As mentioned previously, future experiments will have increased code rates and decreased magnetic field magnitudes. Thus, an operational system with 10 Hz position estimates may involve magnetic fields with strengths on the order of the noise floor, or even lower. Note that this is not an issue as it is quite natural for CDMA signals to be below the noise floor and still fully useable, due to the 'processing gain' of the correlation step [14].

Data, such as that shown in Figure 7, was sent from the sensor unit to a PC for analysis. Using MATLAB, the correlation procedure described in Section 4 was applied to this data. The result was a vector estimate of the field strength caused by each of the 8 beacons in the experiment area.

These field strength estimates were then used to solve equation (5.5) for sensor position. Errors in position coordinate estimates from this step alone had a standard deviation of 8.0 centimeters.

The position estimate obtained from equation (5.5) is then used as a starting point to solve equation (5.4) for sensor position. Errors in position coordinate estimates from this step had a standard deviation of 2.5 centimeters.

Continuing with the algorithms presented in Section 5, the singular value decomposition method [12] was used to solve for the elements in the direction cosine matrix, thus relating the absolute coordinate frame with the sensor coordinate frame. The direction cosine matrix elements were converted into a set of Euler angles. Euler angle estimates were obtained with a standard deviation of 2.5 degrees.

These experimental results include data sets where there was no direct line of sight between sensor and beacons, e.g. the sensor inside a cardboard box or aluminum container. No corrections were made for ferromagnetic material in the area, such as the iron reinforcements in the concrete immediately under the test area.

These accuracy numbers will change as the system is upgraded to produce 10 Hz estimates, as the beacon spacing is increased, and as the beacon electronics are changed to provide closed-loop current control. The value of this initial experiment is in verifying the CDMA methods and algorithms described in this paper, as well as an initial check that it is feasible to obtain the centimeter-level accuracy required for precise positioning of mobile robots.

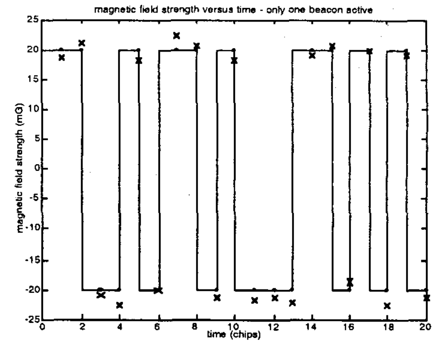

Figure 6. Magnetic field versus time when only one beacon is active. The ('o') marks are theoretical values and the ('x') marks are measured values.

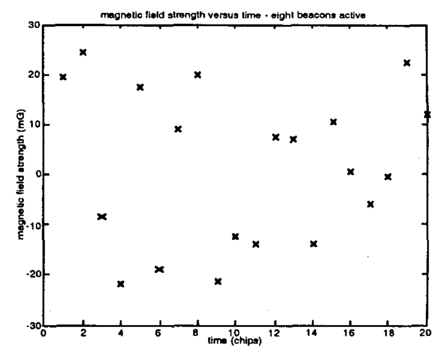

Figure 7. Measured magnetic field strength versus time with eight beacons active.

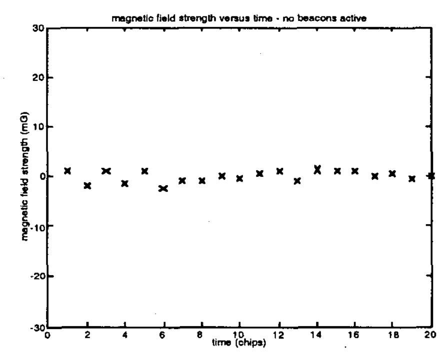

Figure 8. Measured magnetic field strength versus time with no beacons active, showing ambient noise level of approximately 2 mG.

7 Conclusions

This work presents an absolute position and attitude sensing system with no line of sight restrictions and an operating area that can span an entire office building or warehouse. This system not only provides 'go-anywhere' freedom for mobile robots, but has application in other areas such as object and personnel tracking, augmented reality, and motion capture.

A system is described that uses beacons fixed in known locations throughout a building to create dipole magnetic fields. The application of CDMA techniques combines the advantages of the FDMA and TDMA magnetic field technologies, allowing numerous beacons to be active at the same time while retaining the benefits of sampling the magnetic field as it approaches a steady state value. The CDMA method offersintrinsic rejection of common forms of noise. Furthermore, CDMA provides a natural method to greatly increase the number of beacons in the system, resulting in increased coverage area, accuracy, and resistance to distortion. Algorithms are detailed that can be used to calculate position and orientation given magnetic field strengths from several beacons. Finally, initial experimental results verify the methods and algorithms presented.

References

[1] Ascension Technology Corporation, Burlington, VT, "Overcoming Metal Problems: The Advantages of DC Magnetic Tracking," http://www.ascension-tech.com/inthenews/dcadvantage1.htm.

[2] Ascension Technology Corporation, Burlington, VT, MotionStar product brochure.

[3] W. Birkfellner et al. "Systematic distortions in magnetic position digitizers," Med. Physics, vol. 25, no. 11, pp. 2242-2248, 1998.

[4] E. Blood, "Device for quantitatively measuring the relative position and orientation of two bodies in the presence of metals using direct current magnetic fields," U.S Patent #4,945,305, July 31, 1990.

[5] H.R. Everett, D.W. Gage, "From Laboratory to Warehouse: Security Robots Meet the Real World," The International Journal of Robotics Research, vol. 18, no. 7, pp. 760-768, July, 1999.

[6] H.R. Everett, *Sensors for Mobile Robots: Theory and Application,* A.K. Peters, Ltd., 1995.

[7] J. Farrell, J. Stuelpnagel, "A Least Squares Estimate of Satellite Attitude," *SIAM Review*, Vol. 8, No. 3, p. 384, July 1966.

[8] HelpMate Robotics Inc., Danbury, CT, http://users.ntplx.net/~helpmate.

[9] U.S. Inan, A.S. Inan, *Electromagnetic Fundamentals and Applications*, Addison Wesley Longman, 1997.

[10] InterSense, Burlington, MA, IS-900 product brochure.

[11] F. Markley, "Attitude Determination Using Vector Observations: A Fast Optimal Matrix Algorithm," *Journal of the Astronautical Sciences*, Vol. 41, No. 2, p. 261, April-June 1993.

[12] F. Markley, "Attitude Determination using Vector Observations and the Singular Value Decomposition," *Journal of the Astronautical Sciences*, Vol. 36, No. 3, p. 245, July-Sept. 1988.

[13] E.A. Olsen, C-W Park, J.P. How, "3D Formation Flight Using Differential Carrier-phase GPS Sensors," presented at the Institute of Navigation GPS meeting, Nashville, TN, Sept. 18, 1998.

[14] B.W. Parkinson, J.J. Spilker, P. Axelrad, P. Enge, *Global Positioning System: Theory and Applications Volume I*, AIAA, pp. 57-119, 1996.

[15] Ibid., pp. 409-433.

[16] Polhemus, Colchester, VT, StarTrak product brochure.

[17] RedZone Robotics, Inc., Pittsburgh, PA, product information at http://www.redzone.com.

[18] M. Rossetti, A. Kumar, R. Felder, "Investigating Robotic Fleet Incentives for Mid- to Large-Sized Hospital Facilities," Final Report, HelpMate Robotics, available at http:// www.people.virginia.edu/~mr2m/papers.html.

[19] S. Scheding, G. Dissanayuke, E.M. Nebot, H. Durrant-Whyte, "An Experiment in Autonomous Navigation of an Underground Mining Vehicle," IEEE Transactions on Robotics and Automation, vol. 15, no. 1, pp. 85-95, Feb. 1999.

[20] Servus Robots, Richmond, VA, product information at http:// www.servusrobots.com/products.htm.

[21] M. Shuster, S. Oh, "Three-Axis Attitude Determination from Vector Observations," *Journal of Guidance and Control*, p. 70, Jan-Feb 1981.

[22] M. Siegel, P. Gunatilake, "Remote Inspection Technologies for Aircraft Skin Inspection," IEEE Workshop on Emergent Technologies and Virtual Systems for Instrumentation and Measurement, Ontario, Canada, May 15-17, 1997.

[23] S. Thrun, et al. "MINERVA: A second generation mobile tour-guide robot," Proceedings of the IEEE Int. Conf. on Robotics and Automation (ICRA '99).

[24] G. Wahba, "A Least Squares Estimate of Satellite Attitude," *SIAM Review*, Vol. 7, No. 3, p. 409, July 1965.

[25] H.A. Yanco, "Wheelesley, a robotic wheelchair system: indoor navigation and user interface," in *Lecture Notes in Artificial Intelligence: Assistive Technology and Artificial Intelligence*, edited by V.O. Mittal, H.A. Yanco, J. Aronis, and R. Simpson, Springer-Verlag, 1998.