Indoor Navigation for First Responders: A Feasibility Study

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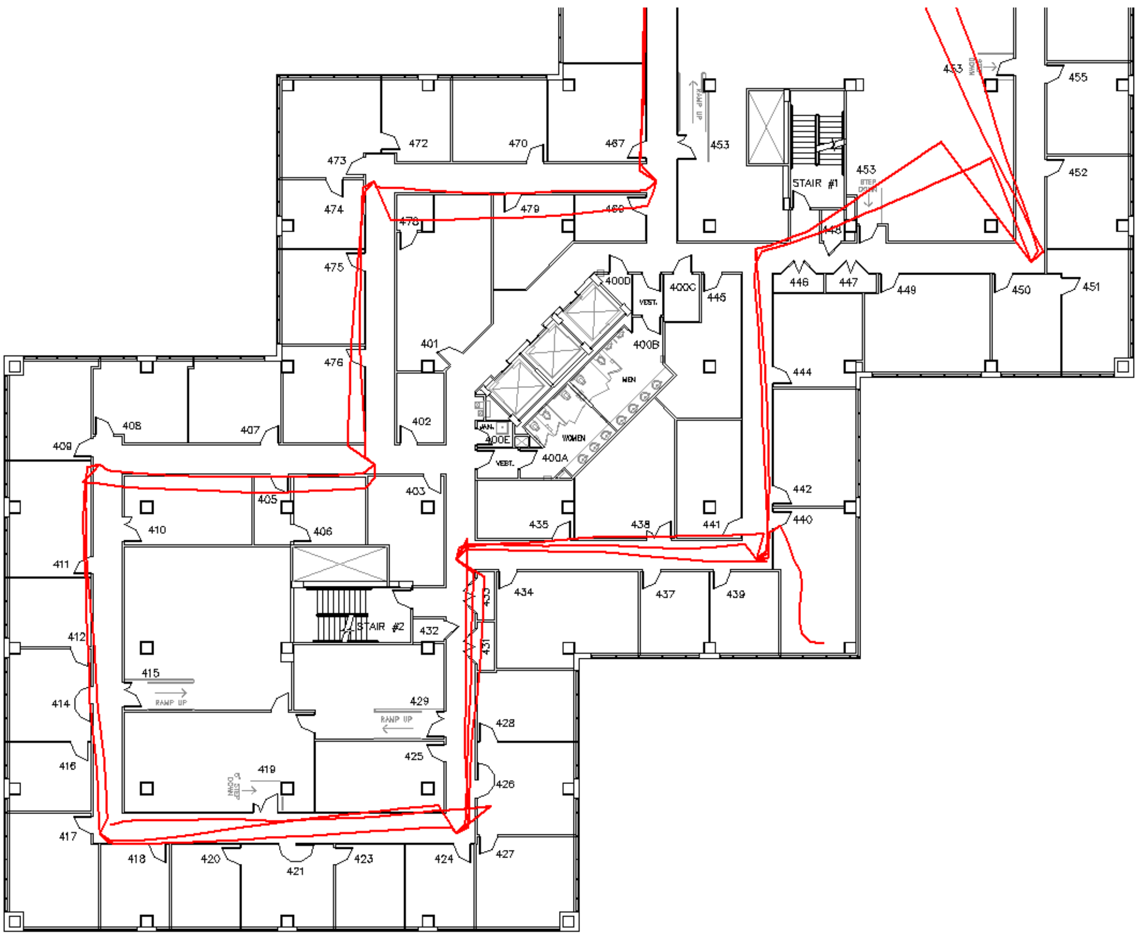
10 February 2006



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1. Introduction

This report describes a study of indoor navigation techniques that took place as part of an overall project for enhancing the ability of tactical teams to track the location of first responders who have been deployed into buildings. In this introductory section, we describe the project, state the concepts that have guided the study, and summarize the technical approach for the project work.

1.1 Overall Project Description

RFID (radio-frequency identification) devices commonly are attached to persons or to moveable objects so that the objects can be tracked using fixed readers (special-purpose radios) at different locations. In this research program, supported in part by the NIST Advanced Technology Program (ATP), we proposed to explore a novel application of the "flip side" of this practice based on the concept that detection of an RFID device in a known, fixed location by a moving reader provides a precise indication of location for tracking the person or moving object that is carrying the reader. The research program was designed to evaluate the exploitation of this concept to implement a low-cost, reliable means for tracking firefighters and other first responders inside buildings, where navigation using GPS is not reliable—indeed, the GPS signal may have been disabled temporarily to prevent exploitation by terrorists [1].

The system envisioned by this proposal is intended for an environment that is potentially much less "friendly" to RF propagation—the in-building environment of first responders that may contain smoke, dust, or flames—and is intended to leverage advances in ubiquitous RFID tag technology, in combination with recent advances in miniaturized inertial sensors, to develop a low-cost tracking system that does not depend upon the stability of the RF environment over relatively large distances to derive range from precision timing. The "philosophy" of the proposed RFID-assisted system also involves reducing the dependence on RF links to external data sources by exploiting the capability of RFID tags to store critical building information for retrieval when it is needed, where it is needed.

1.2 Concepts Guiding the Study

1.2.1 Indoor Navigation Cannot Depend on GPS

As mentioned above, it cannot be assumed that GPS position solutions will be available to first responders in a mission-critical situation. Even without the prospect of having the GPS signals blocked or obscured for tactical advantage, the reception of GPS signals inside most buildings is not reliable.

1.2.2 Inertial Sensors Can Track Location, Motion

In addition to, or in place of, GPS the position of a first responder inside a building can be tracked using inertial sensors such as accelerometers and gyroscopes. As will be discussed in Section 2, non-inertial sensors such as magnetometers and barometers can also be used in conjunction with dead reckoning methods to develop positions of a first responder in motion.

1.2.3 RFID Fixes Can Enhance the Accuracy of Inertial Tracking Systems

Inertial tracking systems inherently drift over time and produce errors in position, especially for inexpensive and lightweight systems. Corrections to the position solution at points along the path of the first responder can limit the maximum error to an acceptable level. Corrections, in the form of the insertion of known locations that have been reached, can be entered manually or they can be developed automatically by the detection of an RFID device, either by correlating the identity of the device with a table of locations or by reading the device's location from data stored on it.

1.3 Approach to the Study

1.3.1 Overall Approach

In addition to assessing the RF (radio frequency) propagation environment of buildings in emergency situations, the overall research program is considering several operational scenarios consisting of (1) the strategy for RFID deployment, (2) the tracking method, and (3) the options for presenting location information to the user and communicating this information to a monitoring station. The RFID deployment and tracking aspects of the scenarios to be studied include:

- The tradeoffs involved in the choice of RFID devices for this application, including cost, ease of programming, suitability for emergency environments, and data capacity.
- Use of relatively few RFID location reference points to correct or calibrate an inertial navigation or other localization system to maintain sufficient accuracy during a first responder incident.
- Use of multiple RFID location reference points to furnish data for tracking without the use of inertial sensors.

The emphasis will be to make maximum use of information and to leverage software to simplify hardware implementations. The presentation and communication aspects of the scenarios to be studied include:

- Informing the user (only) of position (stand-alone mode), assuming any communication is provided by a separate system.
- Informing the user, other team members, and an incident commander of their positions via an ad hoc network of radio terminals that combine RFID reading and radio communication.
- Providing the user with directions for safe exiting of the building.

1.3.2 Approach to the Navigation Techniques Study

The portion of the project that is covered by this report is a study of navigation techniques for potential use in indoor scenarios. For this study, the approach was first to survey navigation techniques and sensors with potential for indoor use. During the performance of the survey, a particular dead reckoning module (DRM) was identified as having good potential for the project's application; therefore, the second part of the study consisted of an evaluation of the DRM in combination with several tracking options.

1.4 Outline of This Report

Following this introduction, the report contains three main sections and a section containing reference material.

In Section 2, the technology of navigation and positioning systems is surveyed to identify techniques and sensors that may be useful for indoor applications.

In Section 3, the experimental indoor use of a DRM for indoor positioning is described with respect to device, scenario, and tracking considerations.

Section 4 contains references cited in the report and a bibliography of additional references that have relevance to the project.

2. Survey of Navigation Techniques

In this section, we first provide background information on the Global Positioning System (GPS) as the standard for position location. This background is followed by a survey of navigation sensors and techniques.

2.1 Background: GPS

The most widely used navigation system today is the Global Positioning System (GPS), which enables position determination through the measurement of time delays of signals from multiple satellites in known (moving) positions; the time delay measurements are based on cross-correlating received satellite signals with local replicas to identify the signals' digital code position in time relative to the common reference. Figure 2.1 illustrates the constellation of GPS satellites, from which it is obvious that the number of satellites that are "visible" at a given location on the earth is a variable.

2.1.1 GPS Requirements

The minimum number of satellites needed to obtain an unambiguous GPS position solution is four, as illustrated in Figure 2.2. If more than four satellites are visible, a better solution may result. Systematic biases in GPS position solutions can be reduced using the technique known as Differential GPS (DGPS), in which corrections that account for local topography are supplied by a reference ground station.

Typical GPS receivers have separate acquisition and tracking modules. First, the signal from the satellite must be acquired, which is accomplished when the receiver is aligned in frequency and code phase with the signal. Once the signal is acquired, the receiver locks onto the signal by entering a tracking mode. If the receiver loses lock on the satellite, the acquisition phase must be repeated. These processes may be time-consuming:

> Acquiring the signal is a slow process. The GPS satellite transmits at a known frequency of 1572.72 MHz. Doppler shift adds ±4.2 kHz to the signal, and the speed of the receiver adds another 2 Hz/mph. In addition, the uncertainty in the receiver's local frequency reference adds another 1.575 kHz for each ppm of oscillator error. This together adds an uncertainty of more than ±4.2 kHz to the signal. The receiver detects the signal by cross correlating (i.e. multiplying) the received signal with a local replica of the code used in the satellite. The product is integrated and a peak correlation signal is obtained. If the frequency or the code-delay (delay between the satellite code and the local replica) is incorrect the peak vanishes. A chip represents one bit of the code. The receiver must search for 1023 possible chips (the code is 1023 chips long, thus 1023 possible code delays) at each frequency bin. The uncertainty in frequency mentioned above creates typically 40 frequency bins. Classical GPS receivers have been designed to dwell for at least one millisecond in each frequency/delay bin, taking a total of 40 (40·1023·1 ms) seconds to search the whole frequency/delay space. [2]

The difficulty in using GPS indoors and in urban "canyons" is that the line of sight to the GPS satellites is obscured or severely attenuated. Without four good satellite signals, the GPS position solution is inaccurate. Also, with weak signals, the GPS receiver continually loses lock and must spend an inordinate amount of time in attempting to acquire the signals.

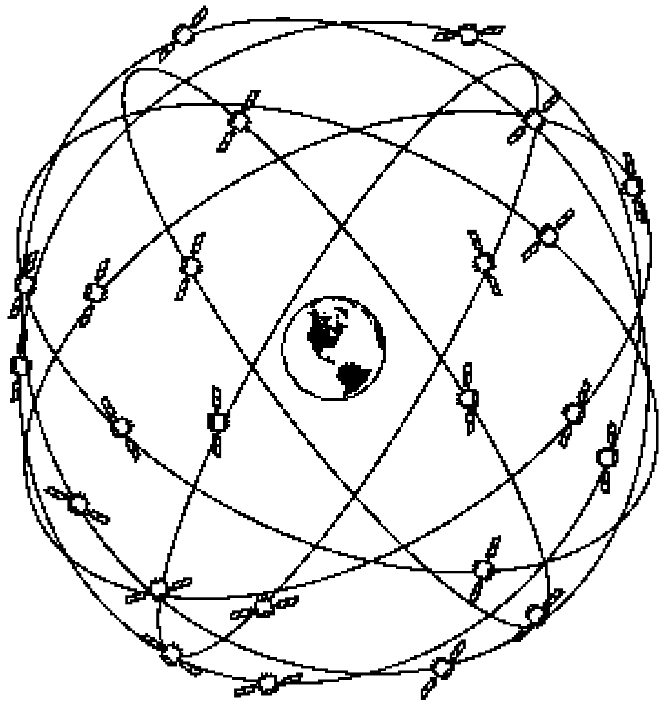


Figure 2.1 Constellation of GPS Satellites (from [3]).

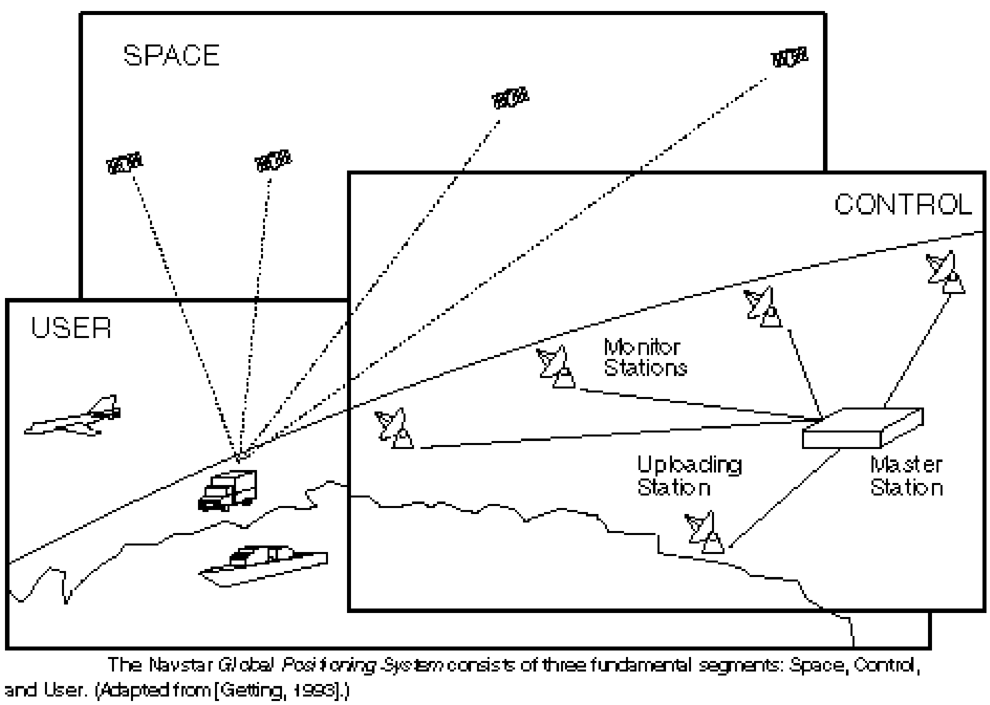


Figure 2.2 Components of the Global Positioning System (from [3], based on [4]).

To increase the likelihood that GPS receivers can operate indoors, where the signal is hundreds to thousands of times weaker than outdoors, an "assisted GPS" system [5] has been developed for cellphones whereby setup information on the available satellites and their Doppler frequency offsets is provided by the base station. At the same time, the cellphone GPS receiver uses a chip capable of massively parallel correlations that increase the sensitivity of receiver to GPS signals by allowing each correlator to observe the signal longer.

2.1.2 GPS Coordinates and Data Conventions

2.1.2.1 Longitude and Latitude

Longitude and latitude provide a coordinate system that describes the location of any point on the surface of the Earth (idealized as a sphere) in degrees. The latitude of a point is defined as its angular distance north or south of the equator with respect to the center of the sphere, ranging from 0° at the equator to ±90° at the north or south pole. The longitude of a point is its angular distance east or west of the Greenwich Meridian. Lines of longitude form great circles (circles having the Earth's radius) running north to south, which seem parallel at the equator but do intersect at the poles. Since the mean radius of the Earth is $r_e = 6378\,\text{km}$ each degree of latitude represents a distance of $2\pi r_e / 360 = 111\,\text{km}$, while each degree of longitude represents this distance only at the equator. The distance for a degree of longitude at a latitude φ above or below the equator equals $\cos\varphi$ times 111 km.

2.1.2.2 World Geodetic System 1984 (WGS84) [6]

WGS 84 is an earth fixed global reference frame, including an earth model. It is defined by a set of primary and secondary parameters:

- the primary parameters define the shape of an earth ellipsoid, its angular velocity, and the earth mass which is included in the ellipsoid reference
- the secondary parameters define a detailed gravity model of the earth.

These additional parameters are needed because WGS 84 is used not only for defining coordinates in surveying, but, for example, also for determining the orbital positions of GPS navigation satellites.

For historical reasons each country has its own geodetic network and national geodetic reference frame. Most of the national reference frames are not identical and are not identical with the global WGS 84 reference frame, as illustrated in Figure 2.3. For practical reasons navigation facilities, e.g. DMEs (distance measuring equipment at airports), are surveyed and coordinated with respect to the national reference frame. The basic problem is to transform the national coordinates to WGS 84 and express all coordinates in this global system. This task is performed by a "geodetic datum transformation."

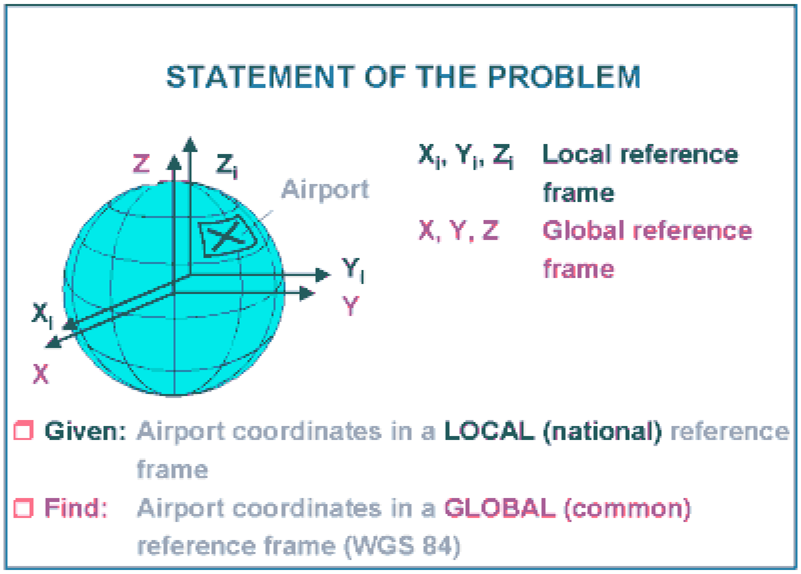


Figure 2.3 Local and global position measurement coordinates are generally different (from [6]).

2.1.2.3 NMEA Data Formats

GPS receiver data output communications are usually formatted according to standards developed by the National Marine Electronics Association (NMEA) that define the interface between various pieces of marine electronic equipment as well as computers. The NMEA format features packets of data called "sentences;" there are standard sentences for each device category and there is also provision for defining proprietary sentences for use by individual companies. A standard sentence has a two-letter prefix that indicates the device using the sentence type (for GPS receivers the prefix is GP), followed by a three-letter sequence that defines the sentence content. An example NMEA GPS sentence is the following [7]:

$GPGGA,123519,4807.038,N,01131.000,E,1,08,0.9,545.4,M,46.9,M,,*47

where:

GGA Global Positioning System Fix Data
123519 Fix taken at 12:35:19 UTC
4807.038,N Latitude 48 deg 07.038' N
01131.000,E Longitude 11 deg 31.000' E
1 Fix quality: 1 = GPS fix (SPS)
08 Number of satellites being tracked
0.9 Horizontal dilution of position
545.4,M Altitude, Meters, above mean sea level
46.9,M Height of geoid (mean sea level) above WGS84 ellipsoid
(empty field) time in seconds since last DGPS update
(empty field) DGPS station ID number
*47 the checksum data, always begins with *

2.1.2.4 UTM Coordinates

For some applications, such as military uses of maps for tactical operations, the Universal Transverse Mercator (UTM) coordinate system is preferred over GPS coordinates. A good explanation of the UTM system is given in [8], from which the following has been extracted:

> In the UTM system, the earth is divided into 60 zones, running north and south, each 6 [minutes (60ths of a degree)] wide. Mapping on flat sheets within one of these narrow zones is satisfactory for all but the most critical needs. Each zone is numbered, beginning with zone 1 at the 180th meridian near the International Date Line, with zone numbers increasing to the east. Most of the United States is included in Zones 10 through 19, as shown in [Figure 2.4]. On a map, each zone is flattened, and a square grid is superimposed upon it. Any point in the zone may be referred to by citing its zone number, its distance in meters from the equator ("northing"), and its distance in meters from a north-south reference line ("easting"). These three figures-the zone number, easting, and northing-make up the complete UTM Grid Reference for any point, and distinguish it from any point on earth. …Figure [2.5] shows a zone, its shape somewhat exaggerated, with its most important features. …The two most important features of the zones are the equator, which runs east and west through its center, and the central meridian, a north-south line through its center. Easting and northing measurements are based on these two lines. The easting of a point represents its distance, in meters, from the central meridian of the zone in which it lies. The northing of a point represents its distance, in meters, from the equator.
>
> …Instead of assigning a value of 0 meters to the central meridian of each zone, each is assigned an arbitrary value of 500,000 meters. Since at their widest points, along the equator, the zones somewhat exceed 600,000 meters from west to east, easting values range from approximately 200,000 meters to approximately 800,000 meters at the equator, with no negative values. The range of possible easting values narrows as the zone narrows toward the poles.
>
> Northings for points north of the equator are measured directly in meters, beginning with a value of zero at the equator and increasing to the north. To avoid negative northing values for points south of the equator, the equator is arbitrarily assigned a value of 10 million meters, and points are measured with decreasing, but positive, northing values heading southward. For clarity, a minus sign usually precedes northing figures for points south of the equator….

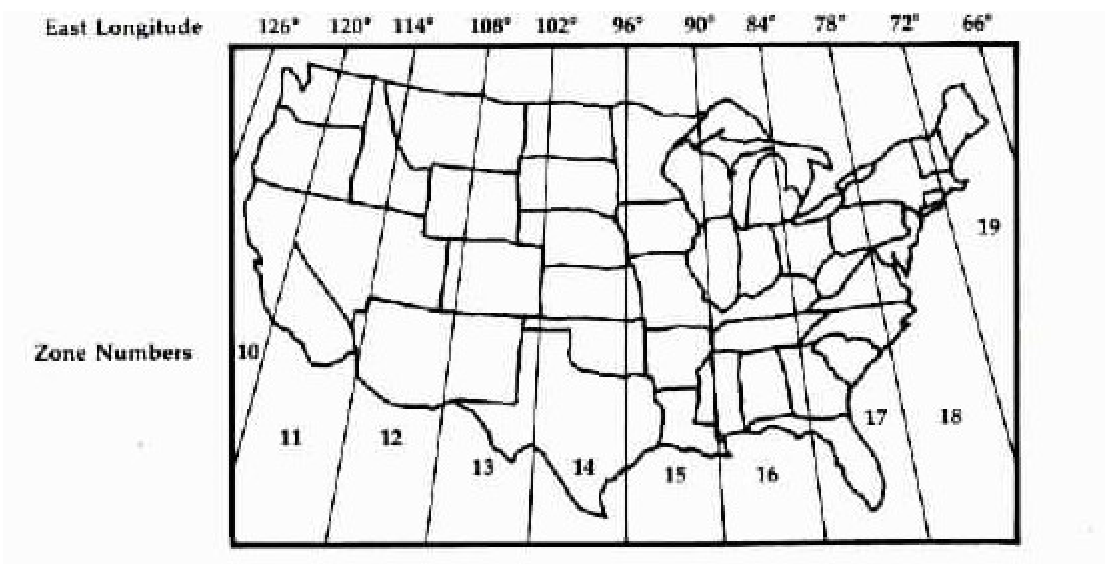


Figure 2.4 UTM zones covering the United States (from [8]).

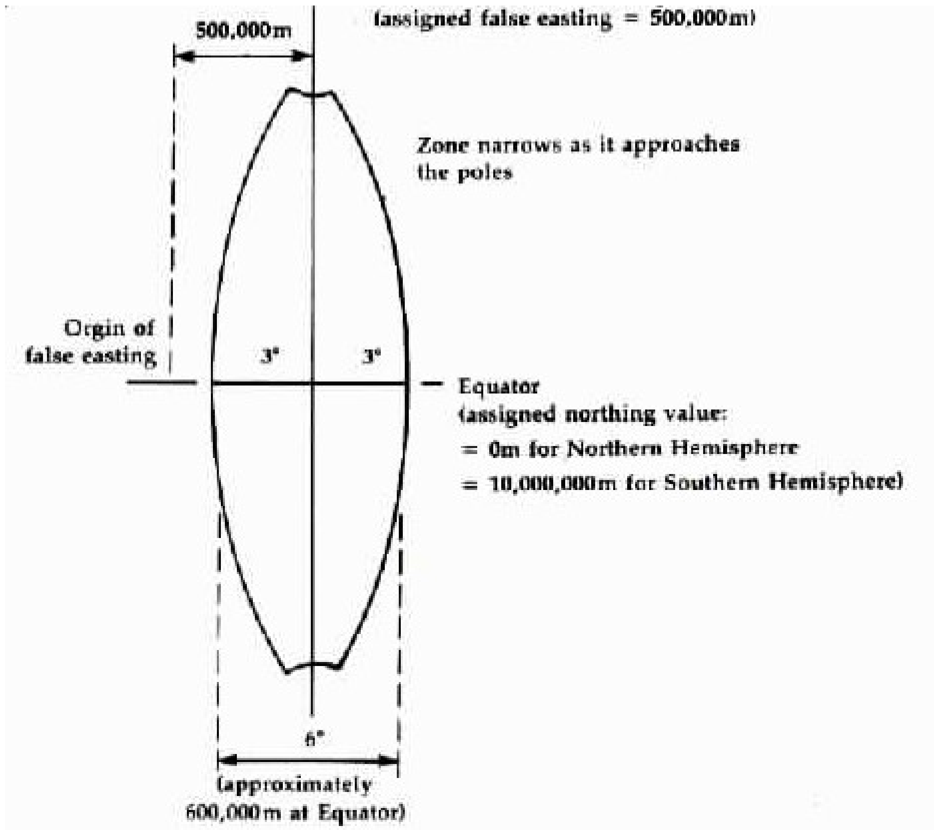


Figure 2.5 Simplified drawing of a UTM sector (from [8]).

2.1.3 Online GPS-Related Tools

There are a number of Internet tools available for developing GPS positions of buildings and possibly within buildings, short of having a professional survey conducted. These include websites that utilize GPS coordinates and/or convert them to UTM coordinates.

2.1.3.1 GPS Coordinates for Fixed Locations

The online search utility "Google" has a mapping search engine that permits the display of points on the Earth using street map data and satellite imagery. For example, the Google display in Figure 2.6 shows the GPS position of a corner of the NIST North building, with latitude 39.14233 degrees North and longitude 77.21455 degrees West. These coordinates were found iteratively by using this web page display to show estimated positions and to "home in" on the desired location using finer and finer corrections to the estimated position.

The satellite imagery illustrated in Figure 2.6 has a finite resolution. Therefore, the ability to develop the GPS coordinates of buildings and locations within buildings by the described method is limited.

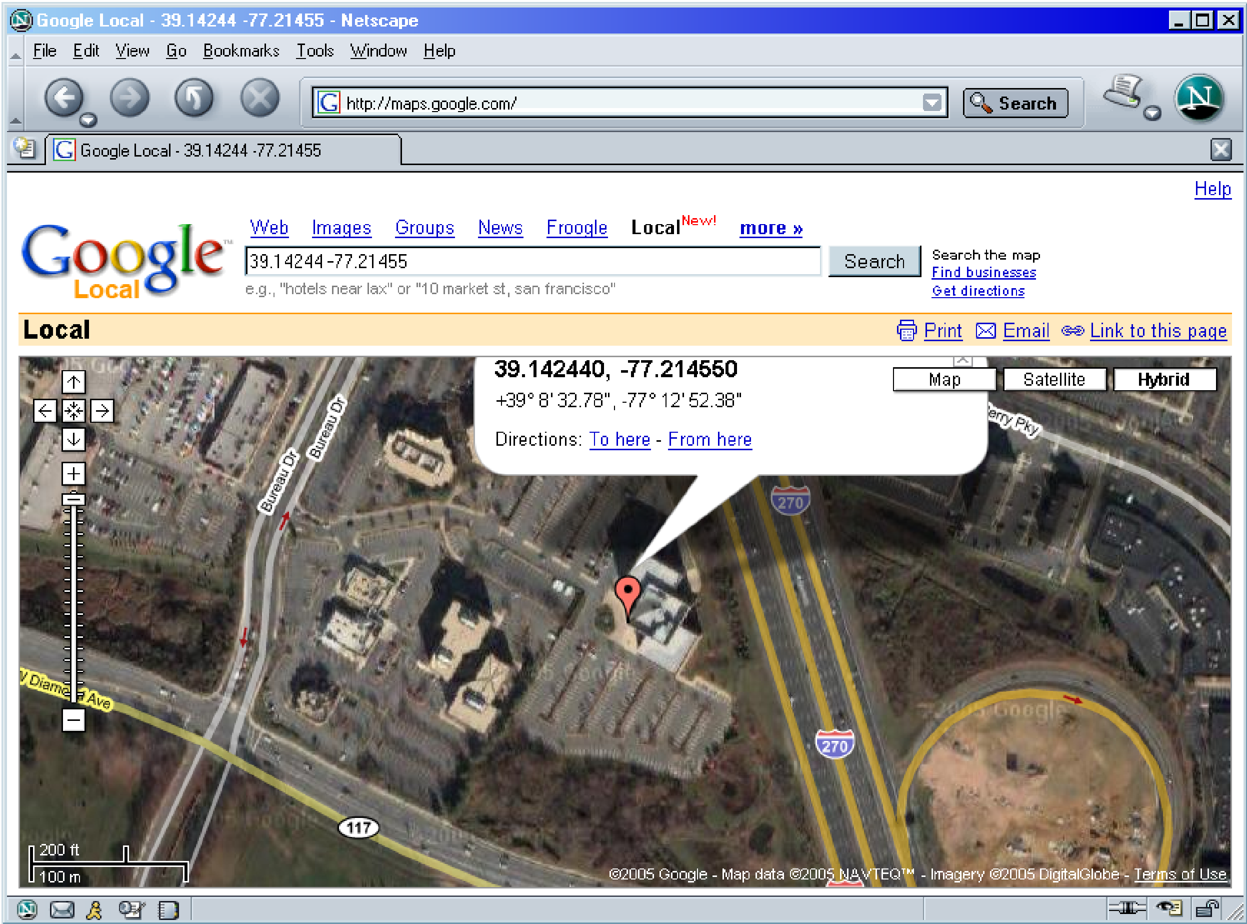


Figure 2.6 Example online GPS coordinates matching building location.

2.1.3.2 Online Coordinate Conversion Tools

The conversion of latitude and longitude to UTM coordinates is desirable in order to work with linear distances within and around buildings. The conversion procedure is not difficult mathematically but has its subtleties in the selection of the specific model of the not-quite-spherical Earth. Fortunately, several convenient online coordinate conversion tools are available.

The Internet web page display of one such tool, at http://boulter.com/gps/ , is shown in Figure 2.7. Note that the page displays the Google map location of the point entered in decimal degrees, in addition to the conversion of latitude and longitude into several different formats, including

- Latitude and longitude in degrees, minutes, and seconds
- Latitude and longitude in degrees and minutes
- UTM zone, northing, and easting.

If it is desired to convert UTM coordinates to latitude and longitude, the coordinate translation calculator at http://jeeep.com/details/coord/, shown in Figure 2.8, is very useful. This calculator

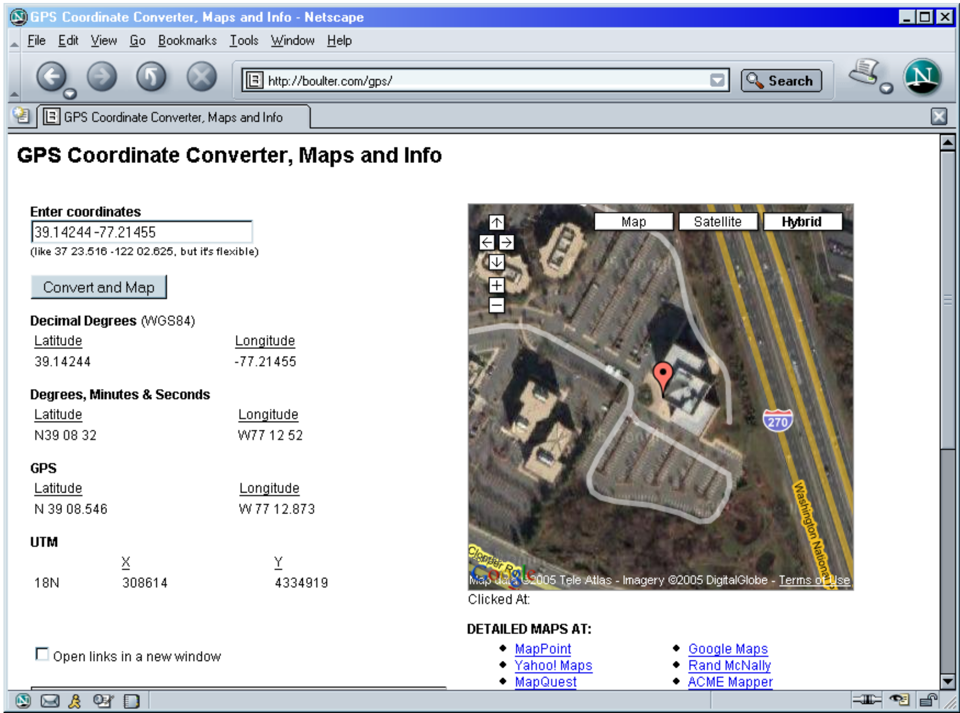


Figure 2.7 Online GPS coordinate converter including map display.

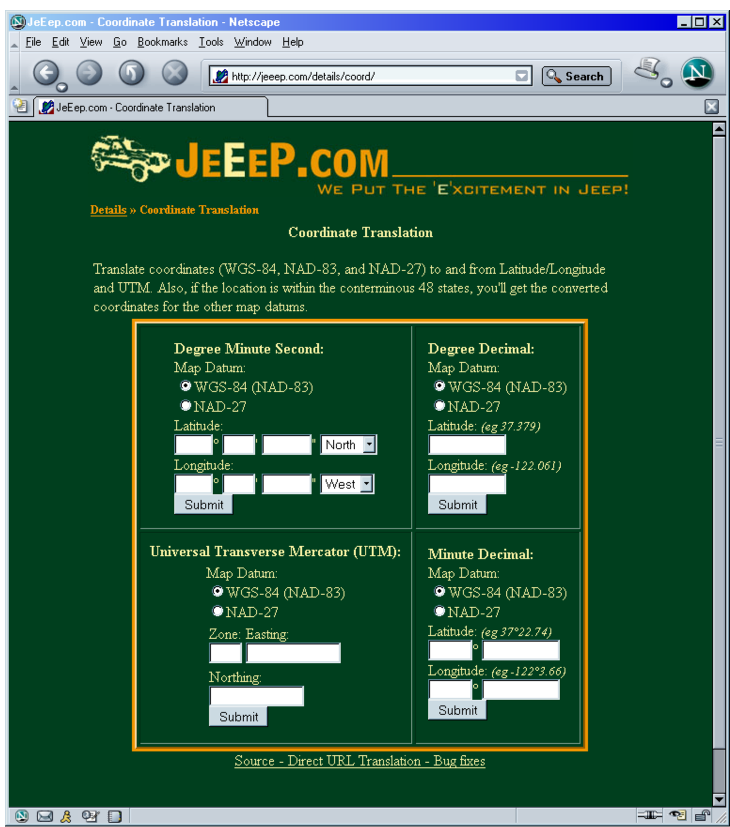


Figure 2.8 Online GPS coordinate translation calculator.

was used in combination with the Google map website to construct the table of locations given in Table 2.1. The resolution and accuracy of these conversions may or may not be satisfactory for indoor navigation systems and their evaluation. UTM coordinates are given in units of meters, and it is not possible to state the (X, Y) position any more accurately using such geophysical methods.

Using the building corner points in Table 2.1, it was determined from the UTM coordinates that the North corner of the NIST North building is approximately 18 meters further west than the South corner. With this information the sketch of the fourth floor of the building that is shown in Figure 2.9 was created. In this sketch, the positions of the waypoints in the hallways that are marked by triangles or stars were determined relative to the southernmost waypoint using a metric scale derived from the UTM coordinates. This development of a geographically oriented depiction of the building was done in anticipation of the evaluation of a compass-based dead reckoning module that is reported in Section 3.

Table 2.1 GPS positions in and around the NIST North building.

Point	[1]Degr Lat	Degr Long	Lat dd mm ss	Long dd mm ss	UTM X[2]	UTM Y
Flagpole	39.14245	-77.21471	N39 08 32.82	W77 12 52.95	308599	4334920
N. Corner	39.142829	-77.21444	N39 08 34.18	W77 12 51.98	308624	4334961
E. Corner	39.142525	-77.214080	N39 08 33.09	W77 12 50.68	308654	4334927
S. Corner	39.142125	-77.2142	N39 08 31.65	W77 12 51.12	308642	4334883
W. Corner	39.14244	-77.21455	N39 08 32.78	W77 12 52.38	308614	4334919
Room 440	39.14251	-77.214095	N39 08 33.03	W77 12 50.74	308653	4334925

2.2 Sensors for Navigation

In what follows, we describe the main characteristics and uses of sensors that are useful for personal navigation. For convenience, the sensors are grouped in two categories, non-inertial and inertial.

2.2.1 Non-Inertial Sensors

Non-inertial sensors include those that measure orientation and position/displacement directly, or from which position may be deduced. Primarily this type of sensor is used in the dead reckoning and waypoint navigation techniques discussed in Section 2.3.

2.2.1.1 Compasses

The type of handheld compass used in orienteering is illustrated in Figure 2.10. The user rotates the compass housing until the desired direction is aligned with the direction of travel arrow, then orients himself or herself so that the compass needle is aligned with North in the compass housing.

[1] Using Google and visually moving the cursor
[2] WGS84; converted at http://jeeep.com/details/coord/

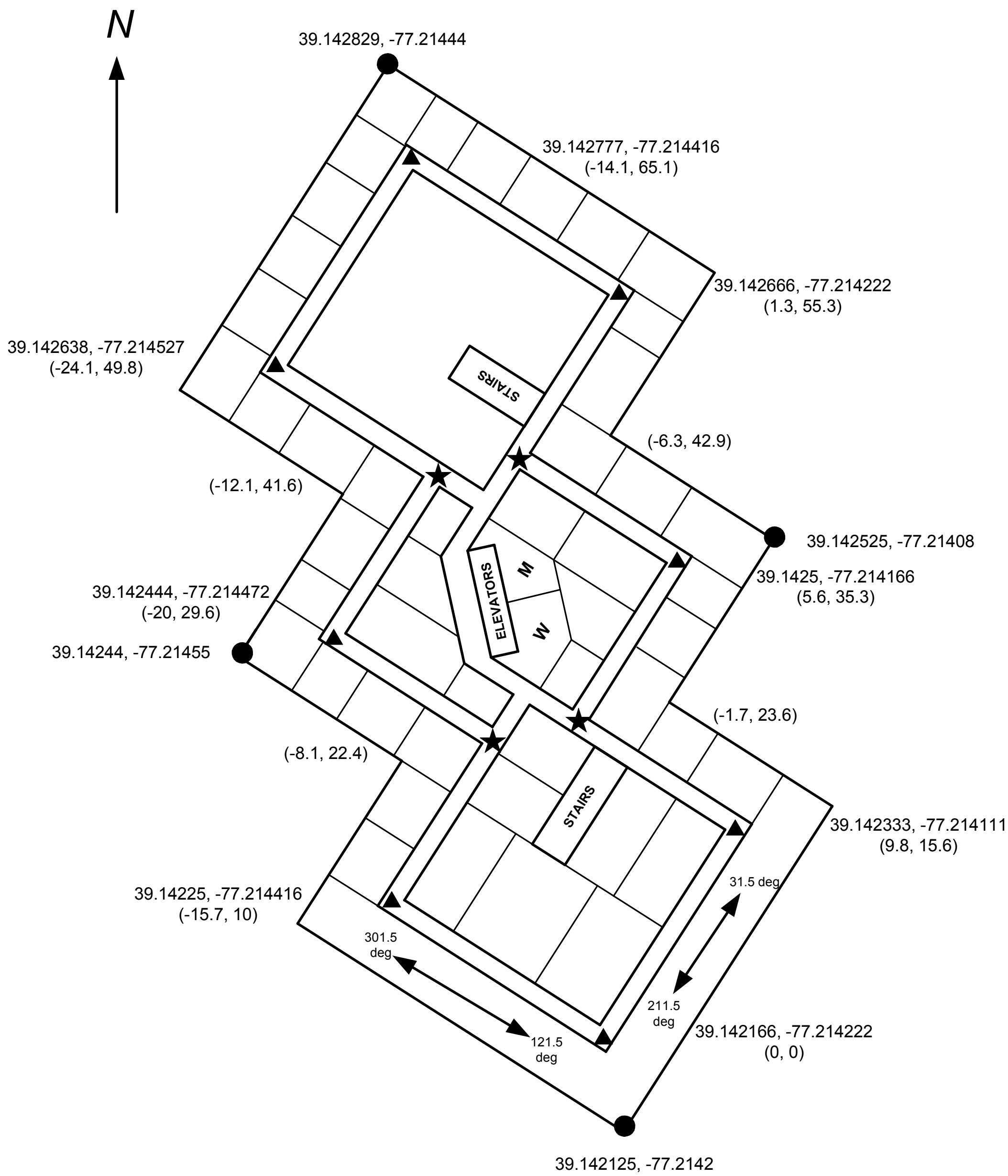


Figure 2.9 Locations in office building based on online GPS data.

> Since the magnetic poles of the Earth do not coincide with the geographic poles, a compass needle in line with the Earth's magnetic field will not indicate true north, but magnetic north. The angular difference between the true meridian (great circle connecting the geographic poles) and the magnetic meridian (direction of the lines of magnetic flux) is called **variation**. This variation has different values at different locations on the Earth [see Figure 2.11]. These values of magnetic variation may be found on pilot charts and on the compass rose of navigational charts. [9]

Electronic compasses based on magnetometers also are available, as discussed in the next subsection.

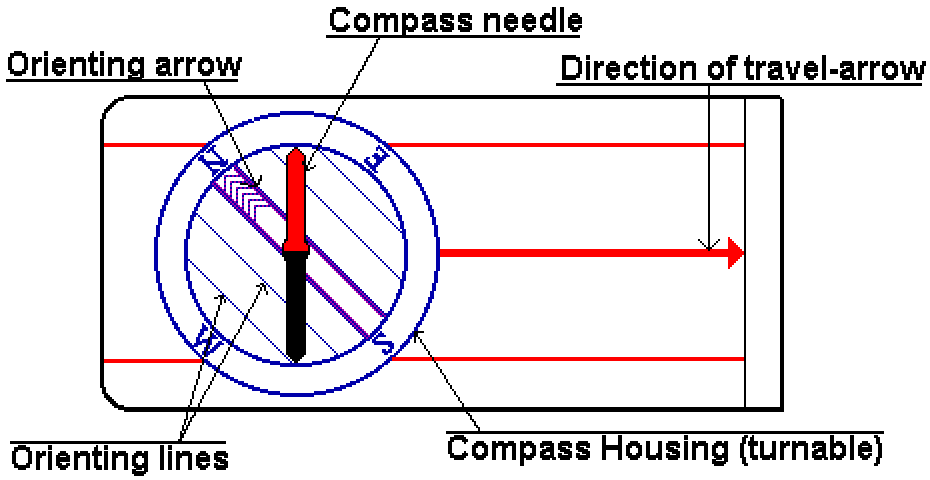


Figure 2.10 Compass used in orienteering (from [10]).

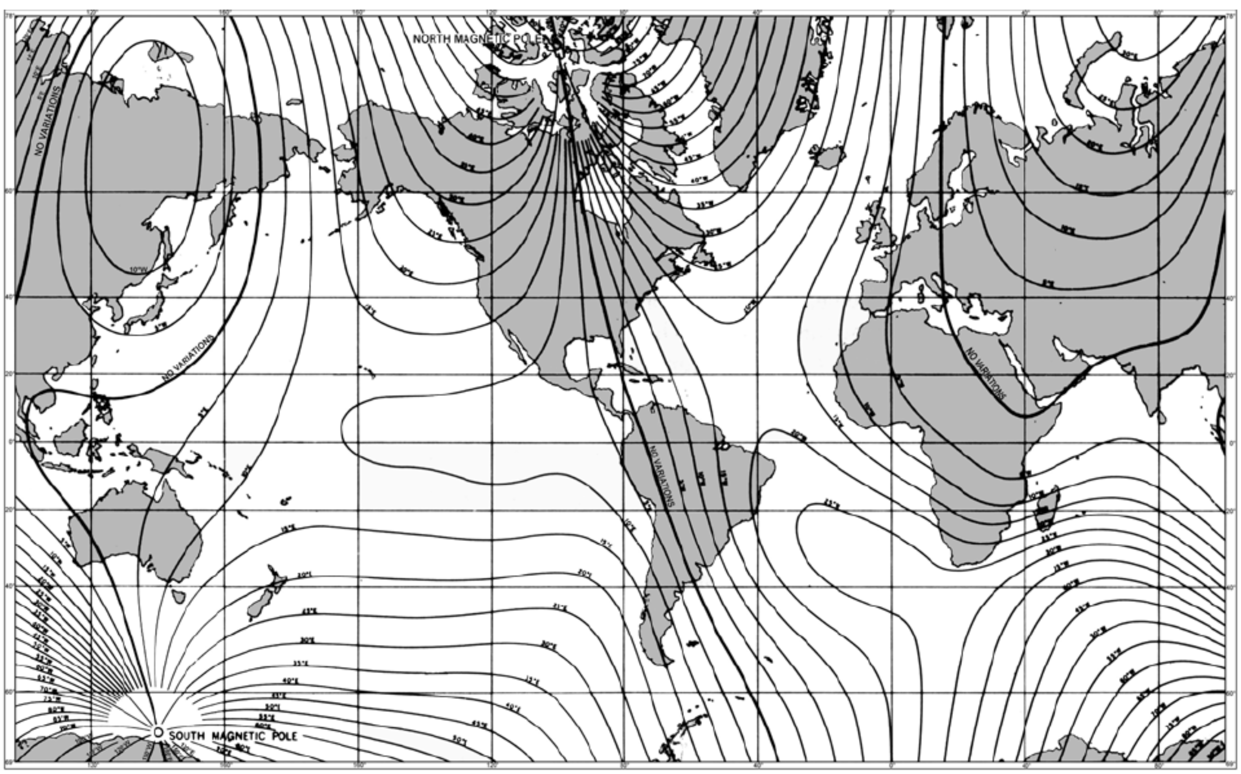


Figure 2.11 Variation in the direction of the Earth's magnetic field from North (from [9]).

2.2.1.2 Magnetometers

A magnetometer is a scientific instrument used to measure the strength of magnetic fields. The Earth's magnetism varies from place to place and differences in the Earth's magnetic field (the magnetosphere) can be caused by such effects as the differing nature of rocks and the interaction between charged particles from the sun and the magnetosphere. Magnetometers are used in geophysical surveys to find deposits of iron because they can measure the magnetic pull of iron. Magnetometers are also used to detect archeological sites, shipwrecks and other buried or submerged objects. A magnetometer can also be used by satellites like GOES to measure both the magnitude and direction of the Earth's magnetic field. [11] Conversely, if the magnetic field has been measured previously, a magnetometer can be used to determine the position that corresponds to the measurement. [12]

Magnetometers can be divided into two basic types: (1) scalar magnetometers that measure the total strength of the magnetic field to which they are subjected, and (2) vector magnetometers that have the capability to measure the component of the magnetic field in a particular direction. The use of three orthogonal vector magnetometers allows the magnetic field strength, inclination and declination to be uniquely defined. [11]

Electronic compasses use vector magnetometer techniques and sensors. For example, two-axis magnetic compasses measure the horizontal vector components of the Earth's magnetic field using two sensor elements in the horizontal plane but orthogonal to each other. Called the X and Y-axis sensors, each sensor on an electronic compass assembly measures the magnetic field in its sensitive axis and the arc tangent Y/X provides the heading of the compass with respect to the X-axis. A two-axis compass can remain accurate as long as the sensors remain horizontal, or orthogonal to the gravitational (downward) vector. In moving platform applications, two axis compasses are mechanically "gimbaled" to remain flat and accurate. [13]

Three-axis magnetic compasses contain magnetic sensors in three orthogonal directions to capture the horizontal and vertical components of the Earth's magnetic field. To electronically gimbal the compass, the three magnetic sensors are complemented by a tilt-sensing element to measure the gravitational direction. The tilt sensor provides two-axis measurement of compass assembly tilt, known as pitch and roll axis. The five sensor inputs are combined to create a "tilt-compensated" version of the X and Y-axis magnetic vectors, and then computed into a tilt-compensated heading. [13]

An example is shown in Figure 2.12 of a three-axis magnetometer assembly that uses solid state magnetic sensors. The assembly diameter is less than three inches.

2.2.1.3 Pressure Sensors

Pressure sensors can be used to sense atmospheric pressure and thereby obtain a measure of altitude. The types of pressure measurements include [15] absolute pressure, measured relative to a perfect vacuum; differential pressure, gauge pressure, measured relative to ambient pressure; and differential pressure, the difference between two points of measurement. Basic types of pressure sensors include [15] potentiometric (resistive), capacitive, and inductive, which measure pressure indirectly as an expansion or contraction of a test device due to pressure; piezoelectric, which develop an electrical charge proportional to pressure; and strain gauges, which convert stresses on materials due to pressure into electrical units.

Figure 2.12 Three-axis magnetometer using solid state magnetic sensors (from [14]).

Any instrument that measures air pressure is a barometer [16]. Atmospheric pressure on the Earth's surface varies from about one kilogram per square centimeter (1013 millibars or 100 kiloPascals [kPa]) to less than one-fifth that amount at an altitude of ten kilometers. Therefore a sensor that can measure pressures up to 100 kPa is useful for altitude measurement. Semiconductor piezoresistive pressure sensors are available for this purpose [17].

2.2.2 Inertial Sensors

Inertial sensors include those that measure force and from it develop acceleration, velocity, and displacement. We also include in this category sensors that use inertia to maintain position or orientation, deviations from which provide information on motion.

2.2.2.1 Accelerometers [18]

Accelerometers are sensing transducers that provide an output proportional to acceleration, vibration, and shock. The piezoelectric accelerometer is the most popular class of these devices; other types are based on piezoresistive, capacitive, and servo technologies.

Piezoelectric accelerometers are self-generating devices that are characterized by an extended flat-frequency response range, a large linear amplitude range, and excellent durability. Piezoelectric materials, whether natural quartz or man-made ceramic, have the ability to output an electrical signal proportional to applied stress. There are two categories of piezoelectric accelerometers, defined by their mode of operation. Internally amplified, or *integral electronic piezoelectric (IEPE)* types, have built-in microelectronic signal conditioning. *Charge-output* devices incorporate only the self-generating piezoelectric sensing element and have a high-impedance charge output signal.

Piezoresistive accelerometers exploit anisotropic properties of single-crystal materials whose atoms are organized in a lattice having several axes of symmetry. A fabrication process developed in the late 1970s takes advantage of advances in silicon micromachining to manufacture MEMS strain gauges that are interconnected as a Wheatstone bridge that gives them a response down to DC (i.e., they respond to steady-state accelerations). An example piezoresistive accelerometer product is shown in Figure 2.13.

Capacitive accelerometers are similar in operation to piezoresistive accelerometers in that they measure a change across a bridge circuit. Rather than resistance, however, they measure a change in capacitance. The sensing element consists of two parallel plate capacitors acting in a differential mode. They rely on a carrier demodulator circuit or its equivalent to produce an electrical output proportional to acceleration. Capacitive accelerometers require a built-in circuit that serves two functions: It allows changes in capacitance to be useful for measuring both static and dynamic events, and it converts the changes into a voltage signal compatible with readout instrumentation. Capacitive MEMS accelerometers measure acceleration from <2 g's to hundreds of g's and frequencies up to 1 kHz, and can withstand shock levels of 5000 g's or greater. Most incorporate electronics that inject a signal into the element, complete the bridge, and condition the signal. The negative aspects of these accelerometers are a limited high-frequency range, a relatively large phase shift, and a higher noise floor than a comparable piezoelectric type.

Servo (force balance) accelerometers are "closed-loop" devices, virtually eliminating errors due to nonlinearities. Electromagnetic forces, proportional to a feedback current, maintain the mass in a null position. As the mass attempts to move, a capacitive sensor detects its motion. A servo circuit derives an error signal from this sensor and sends a current through a coil, generating a torque proportional to acceleration and keeping the mass in a capture or null mode. Servo accelerometers can cost up to 10 × the price of open-loop types. Their ranges are usually <50 g, and they are accurate enough for use in guidance and navigation systems. For navigation, three axes of servo accelerometers are typically combined with three axes of rate gyros in a thermally stabilized, mechanically isolated package as an inertial measuring unit (IMU). This IMU enables determination of the six degrees of freedom needed for navigation in space. They measure frequencies to DC (0 Hz), and are not usually sought after for their high-frequency response.

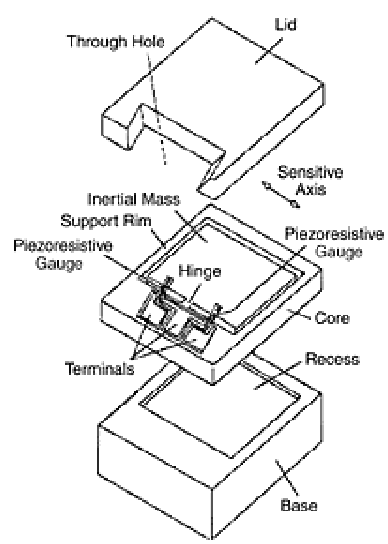


Figure 2.13 MEMS piezoresistive accelerometer (from [18]).

2.2.2.2 Gyroscopes

A gyroscope is an inertial device that reacts to a change in orientation and can be used either to maintain the orientation or to report the change. The major types of gyroscopes from the point of view of technology are spinning mass, vibrating (Coriolis), and optical "gyros." [19] The operation of the classical spinning mass gyro, illustrated on the left side of Figure 2.14 with a gimbal arrangement that allows the spinning mass free movement, is explained as follows [20]:

> Regardless of how the fork is placed, the spinning gyro wheel is free to lie in any given plane. …To show the effect of precession, we can push down on the gimbal ring at point A at the nearer end of the Z-Z axis. You might expect the ring to tilt around the Y-Y axis. Instead, the gyro case will tilt about the Z-Z axis. You can see the effect of this precession [on the right side of Figure 2.14]. Here's a rule that applies to all spinning gyros: THE GYRO WILL ALWAYS PRECESS AT RIGHT ANGLES TO THE DIRECTION OF THE APPLIED FORCE. …If we keep pushing down on the gimbal ring at point A, the gyro case will keep turning until the spin axis of the gyro wheel is horizontal. Then there will be no further precession. At this point the gyro wheel will be spinning in the same direction in which the applied force is pushing. Here's another rule: A GYRO ALWAYS PRECESSES IN A DIRECTION TENDING TO LINE ITSELF UP SO THAT ITS ROTOR SPINS IN THE SAME DIRECTION THAT THE APPLIED FORCE IS TRYING TO TURN IT. …By applying the right amount of force in the right place, we have a method of "aiming" the spin axis so that it points to the specific fixed direction in space where we want it. …Any force acting through the center of gravity of the gyroscope does not change the angle of the plane of rotation but moves the gyroscope as a unit. The position of its spin axis in space is not changed. Such forces as those stated above, operating through the center of gravity, are forces of TRANSLATION. In other words, the spinning gyroscope may be moved freely in space by means of its supporting frame.

Since the precession responds to forces against the spin axis and is orthogonal to it, a spinning gyro can be used to sense the angular movement of its platform. As illustrated in Figure 2.15, in this "rate gyro" mode, the force of the precession, which can be measured at an "output axis," is proportional to the angular rate of the movement about the "input axis."

The physical principle of a *vibrating gyro* is very simple: a vibrating object (such as a tuning fork) tends to keep vibrating in the same plane as its support is rotated. It is therefore

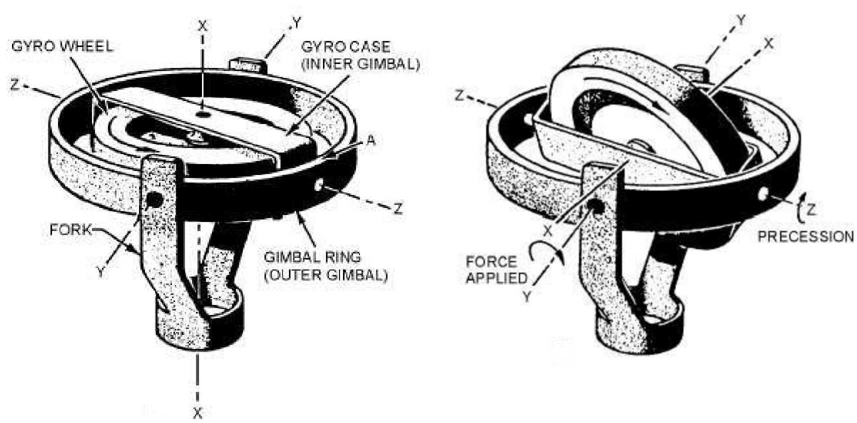


Figure 2.14 Precession of a "free" gyro wheel in response to a rotational force (from [20]).

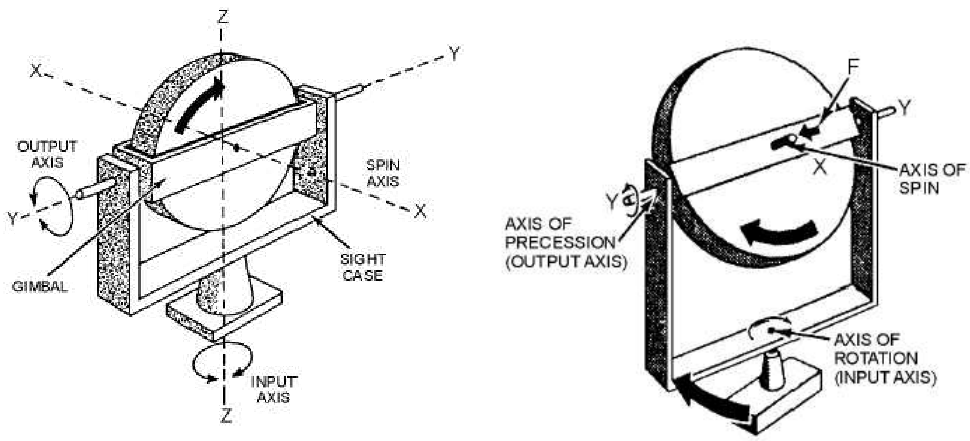


Figure 2.15 Rate gyro operation (from [20]).

much simpler and cheaper than is a conventional rotating gyroscope of similar accuracy. In the engineering literature, this type of device is also known as a *Coriolis vibratory gyro* because as the plane of oscillation is rotated, the response detected by the transducer (usually a piezoelectric device) results from the coriolis term in its equations of motion. [21] Micro-machined (MEMS) rate gyros based on vibration are available; a diagram of a semiconductor rate gyro based on a MEMS tuning fork is shown in Figure 2.16.

An *optical gyro* senses the change in delay of a laser emission over an optical path (*e.g.*, mirrors or fiber) that is due to rotation of its enclosure.

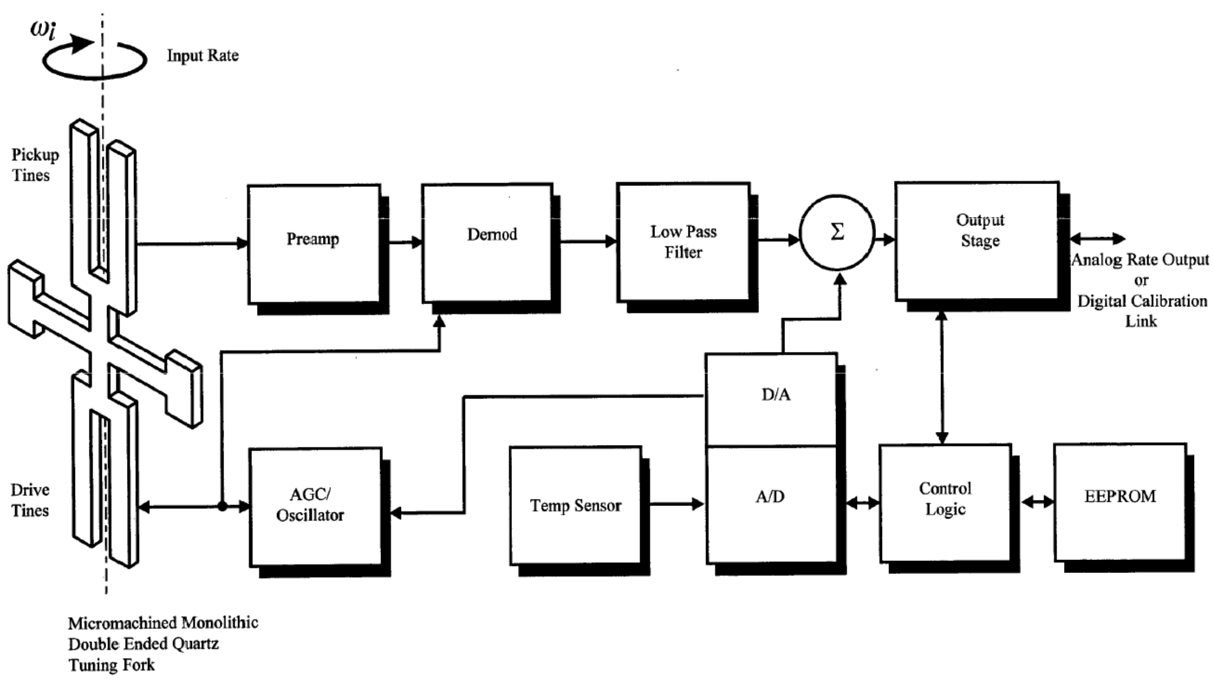


Figure 2.16 Block diagram of a semiconductor gyro based on MEMS technology (from [22]).

2.2.2.3 Inertial Measurement Units

Accelerometers and gyroscopes are often combined as an inertial measurement unit (IMU). When further combined with a control system, the IMU becomes the critical component of an inertial navigation system (INS). Two options for mounting the IMU are shown in Figure 2.17: (a) in a gimbaled system, the IMU sensor outputs are processed by a control system to keep the IMU platform's orientation constant using servo motors, the orientation of the vehicle or other carrier of the INS being inferred from the control signals; (b) in a strapdown system, the IMU sensor outputs are taken as a direct measure of the orientation of the vehicle.

In recent years, there have been many efforts to integrate IMUs with GPS for robotic, aviation, munitions, or vehicular navigation purposes (see [24]–[26]). Most of these efforts have focused on providing a means for preserving a GPS-derived navigation solution during periods in which GPS signals are not available. However, some of the efforts have been concerned with finding a low-cost navigation solution using a MEMS-based IMU, using GPS for calibration and correction. A few combined IMU/GPS products are available (see [27]–[29]).

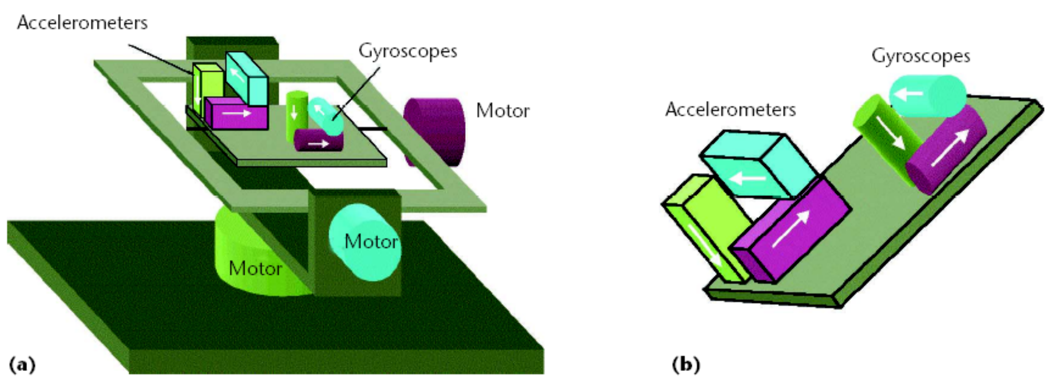


Figure 2.17 Inertial Measurement Units (IMUs): (a) gimbaled (b) strapdown (from [23]).

2.3 Navigation Techniques and Systems

In the following subsections, we describe several navigation techniques and systems that are based on the use of one or more sensors. For some of the systems, there are accelerometers and other inertial sensors involved, but not directly in the determination of position.

2.3.1 Dead Reckoning

"Dead Reckoning is the process of estimating your position by advancing a known position using course, speed, time and distance to be traveled. In other words, figuring out where you will be at a certain time if you hold the speed, time and course you plan to travel." [30] The usefulness of the technique depends upon how accurately speed and course can be maintained on a given "tack;" in the air and on the sea, the selection of fixed speed and course for relatively long periods of time are feasible, while on land or inside buildings the duration of the tack may need to be relatively short due to maneuvers that are required by the terrain or building layout.

As illustrated in Figure 2.18, the uncertainty of the dead reckoning (DR) position grows with time, so that it is necessary to check the position regularly with a “fix” of some kind. One kind of fix is to correct the calculated DR position with an estimate of position based on the directions to three objects in known locations, as depicted in Figure 2.19.

Various systems are being proposed for “pedestrian navigation” utilizing DR techniques and small compasses. For example, [32] describes a small DR unit that utilizes a two-axis compass, a three-axis compass, or a rate gyroscope to track a walking person’s heading. These sensors all describe orientation and therefore are not “inertial” sensors. The sensitivity of the heading produced by these orientation sensors to pitch and roll (deviations from a level attitude) are shown in Figure 2.20; as expected, the heading produced by the 3-axis sensor is least affected by deviations in the person’s attitude. For computation of speed (actually, displacement as a function of time), the system in [32] uses an accelerometer to detect the person’s steps; on average, the distance covered by a step was found to be quite consistent, even though the detection process can be rather subtle:

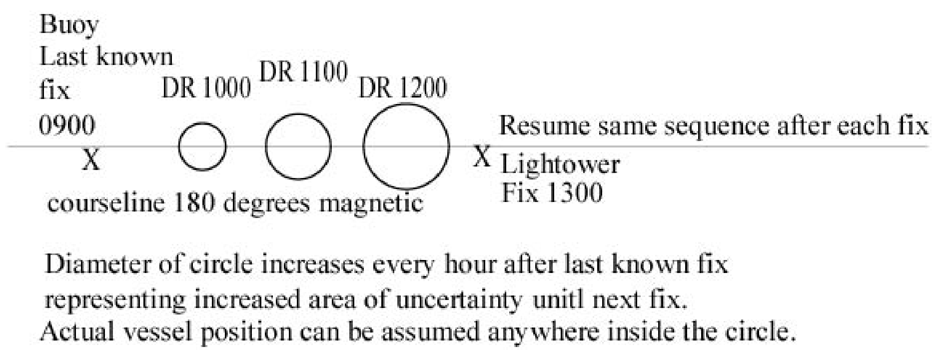


Figure 2.18 Dead Reckoning with open ocean (from [31]).

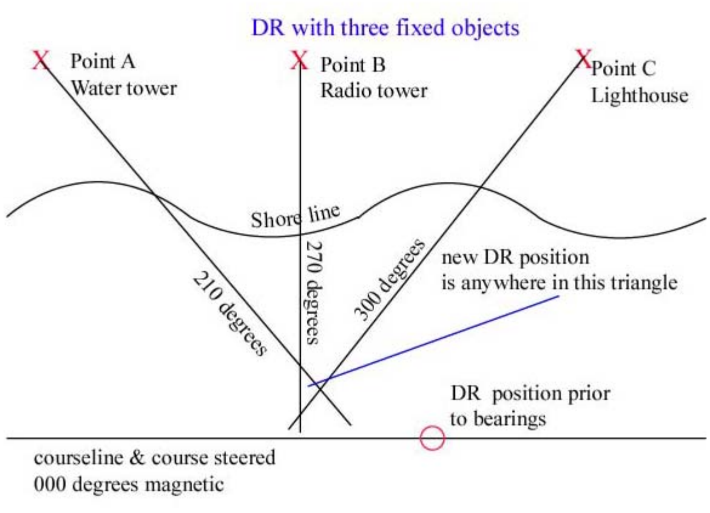


Figure 2.19 Correcting DR position with fixes to known locations (from [31]).

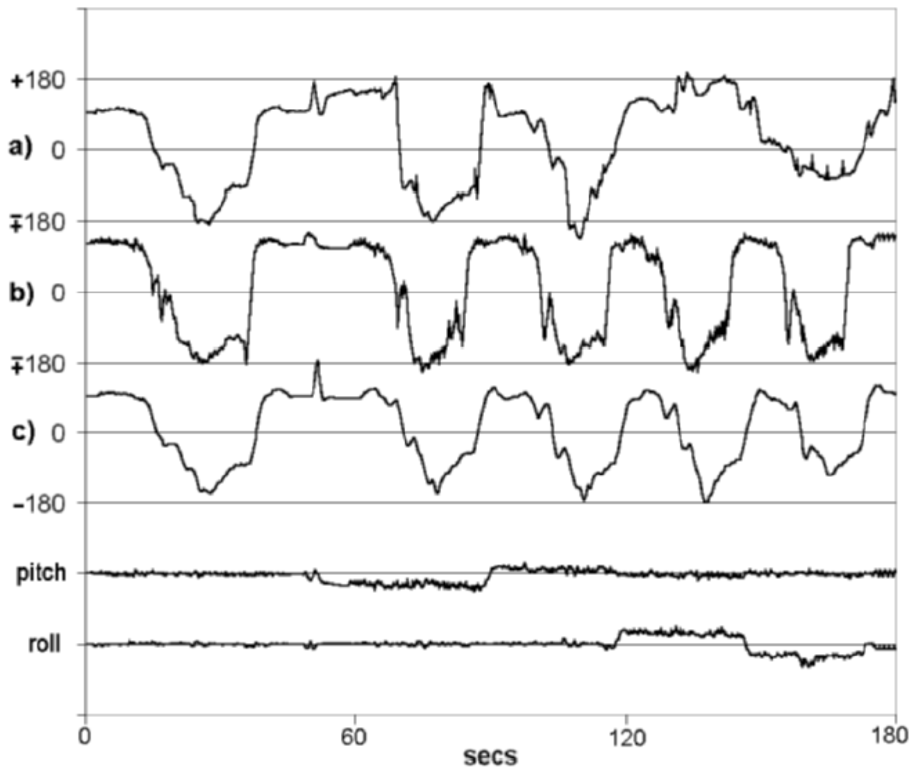


Figure 2.20 Effect of pitch and roll on orientation sensors: (a) 2-axis compass, (b) 3-axis compass, and (c) rate gyroscope (from [32]).

> A greater understanding of the movements and forces was required and a more detailed analysis of the motion of the feet was carried out. Also, since every step is independent of any other then we believed that it would be possible to realise an improvement over the systems that employ step frequency analysis as a means of deducing current speed across the ground. This event driven approach could also prove valuable in analysing disjointed steps that occur when altering course and changing speed…. An important point is that when humans stride further, apart from just stretching out the legs further, the feet move faster for stability reasons…. Hence, it is postulated that the acceleration of the foot (in the vertical plane rather than in the direction of motion) is greater when the foot makes a larger stride. It is this hypothesis that allows us to deduce that the greater the vertical acceleration of the foot during a step, the greater the distance that was traveled across the ground….
>
> Another observation is that humans rarely under-step their minimum average stride again for stability reasons…except for when they are turning on the spot which does not affect distance across the ground). In using this stride length scaling technique based on step energy we can analyse the variations in the raw acceleration data rather than rely on noise intolerant integration techniques.

The performance of the system in [32] with a 2-axis magnetic compass and step detection using an accelerometer in an urban "tourist area" test is shown in Figure 2.21 in comparison to GPS. The scales in the figure are in meters. Although the DR positions were generally in agreement with those developed by GPS, they were often significantly different, due in part to unknown magnetic effects along the path, probably from the presence of an underground electric utility substation along the path. The standard deviation of the position area for the test was about 20 m. The authors conclude, "This case illustrates the susceptibility of magnetic compasses to localized magnetic fields, particularly in an urban environment. In these circumstances a gyroscope solution is clearly advisable."

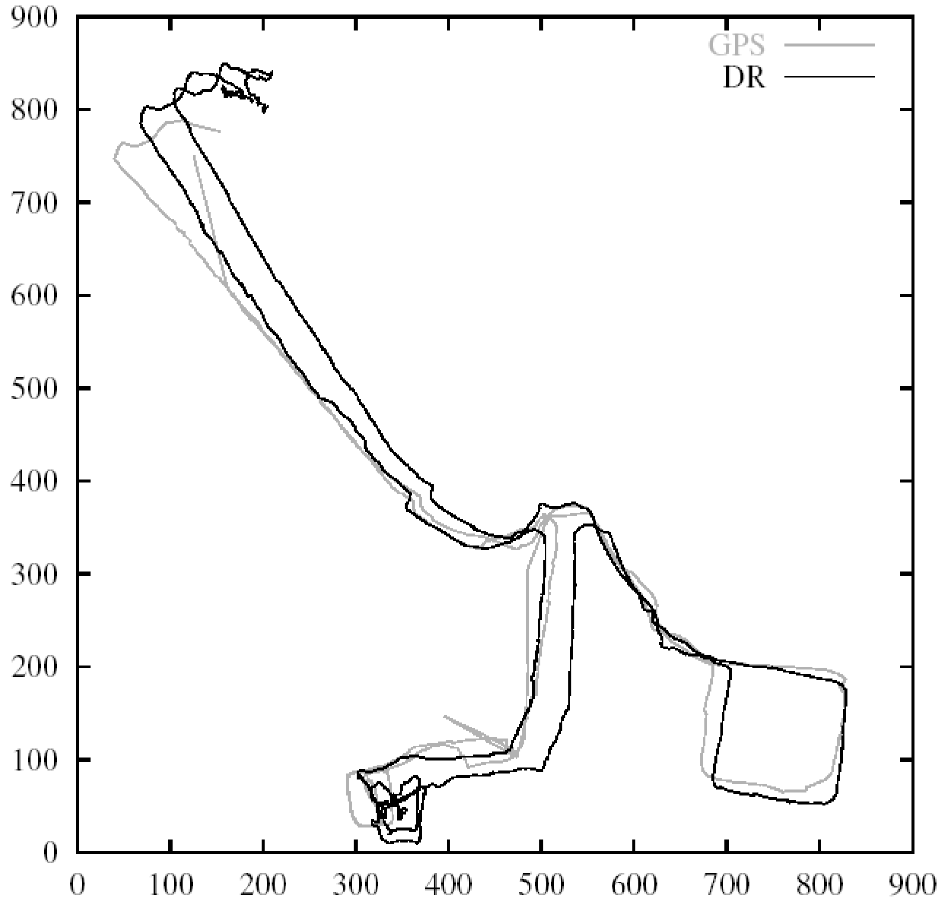


Figure 2.21 Positions developed by a DR system vs. GPS over a 4 km urban trail (from [32]).

Another personal navigation product based on dead reckoning and step counting is the Point Research Corporation's[3] Dead Reckoning Module (DRM), which integrates a GPS receiver with a magnetic compass and other sensors [33–36] and is described as follows:

> The Dead Reckoning Module (DRM®) is a miniature, self-contained, electronic navigation unit that provides the user's position relative to an initialization point. The DRM® is the first commercially available practical implementation of a drift-free dead reckoning navigation system for use by personnel on foot. It is specifically designed to supplement GPS receivers during signal outages. You still know where personnel are located even when GPS is blocked by nearby buildings, heavy foliage, or even inside many structures. The DRM contains a tilt-compensated magnetic compass, electronic pedometer and barometric altimeter to provide a continuous deduced position. A microprocessor performs dead reckoning calculations and includes a Kalman filter to combine the dead reckoning data with GPS data when it is available. The filter and other proprietary algorithms use GPS data to calibrate dead reckoning sensors for a typical dead reckoning accuracy of 2% to 5% of distance traveled, entirely without GPS. Options for the system integrator include a selection of voltage input ranges, CMOS or RS232 interface, data logging, and special software functions. In addition to horizontal position data, compass azimuth, tilt (pitch and roll), and barometric altitude are available. [34]

[3] Point Research Corporation was recently acquired by Honeywell.

The performance of the DRM in comparison to GPS is illustrated in Figure 2.22 for a test in downtown Los Angeles. For improved stability and accuracy, a version of the DRM can be obtained that includes a gyroscope. Figure 2.23 shows an example of improved DRM performance when and gyro is added to it.

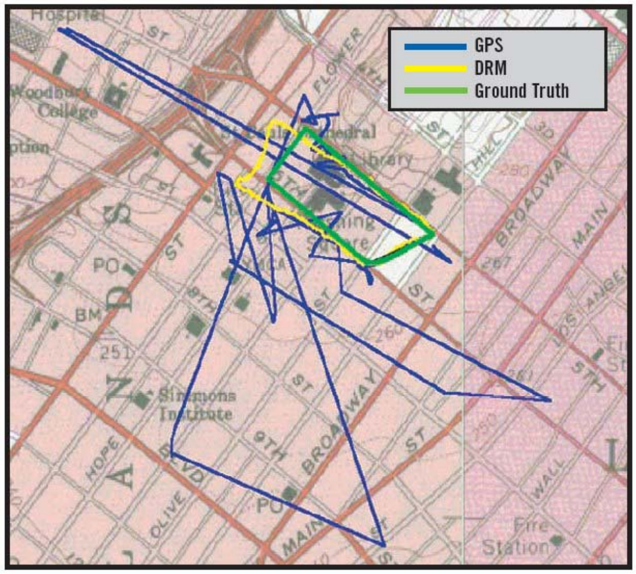


Figure 2.22 DRM positions are useful when GPS is inaccurate or unavailable (from [35]).

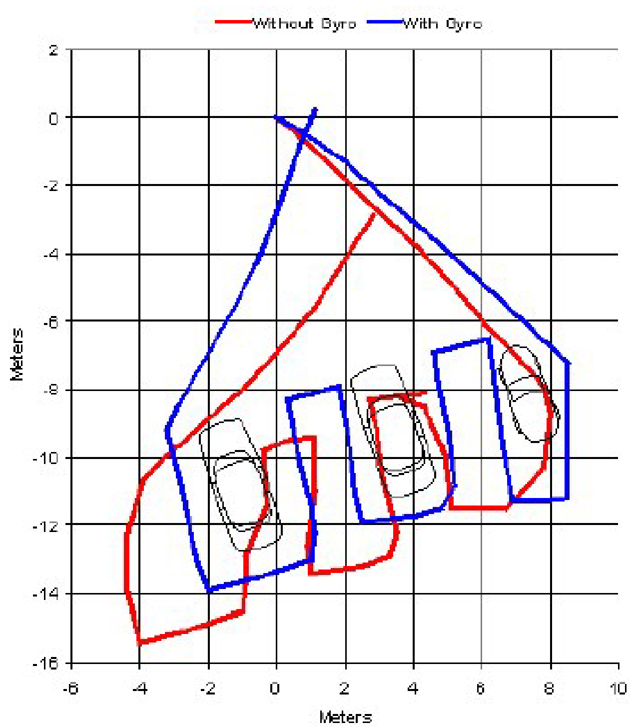


Figure 2.23 Improvement of DRM solution using gyroscope (from [36]).

2.3.2 Waypoint Navigation

A waypoint is a fixed location with known longitude and latitude and UTM coordinates. A modern GPS-enabled navigation system is capable storing a database of waypoints for the following purpose [37]:

> Waypoints mark a destination, a point along the way to a destination, or a point of reference. In navigating with a [GPS-equipped navigation device], a "route" normally consists of one or more waypoints. To traverse a route, the GPS user navigates to the nearest waypoint, then to the next one in turn until the destination is reached. Most units have the ability to compute a great-circle route towards a waypoint, enabling them to find the shortest route even over long distances. Many GPS units, both military and civilian, now offer integrated cartographic databases, enabling users to locate a destination on a map and define it as a waypoint. Some GPS systems intended for automobile navigation can generate a suggested driving route between two waypoints, based on the cartographic database. As one drives along the route, the system indicates the driver's current location and gives advance notice of upcoming turns.

Note that the actual navigating between waypoints depends on techniques such as dead reckoning or GPS-aided navigation.

In [38], the performance of an indoor positioning system based on step counting is evaluated. Figure 2.24 illustrates the traces of accelerometers used to detect the steps made by a person walking a known path indoors, from which the distance traveled is deduced according to simple dead reckoning; the path is shown in Figure 2.25, which also indicates known positions that are used as waypoints. The concept of using the distance between waypoints to correct the distance deduced by counting steps is suggested in Figure 2.24 as well.

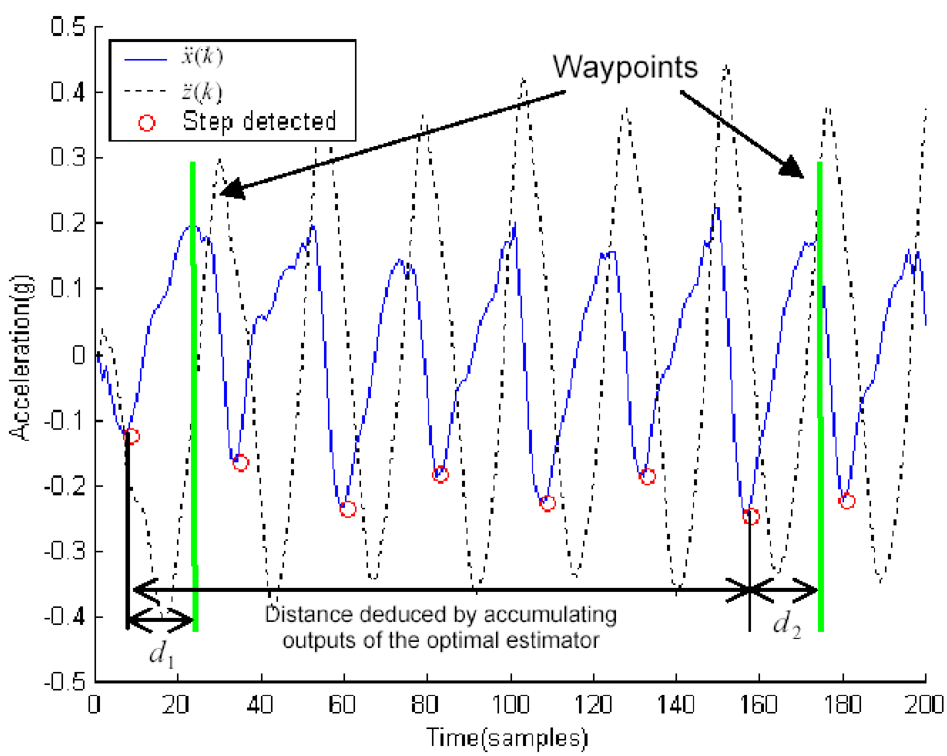


Figure 2.24 Use of waypoints to correct distance estimated from steps (from [38]).

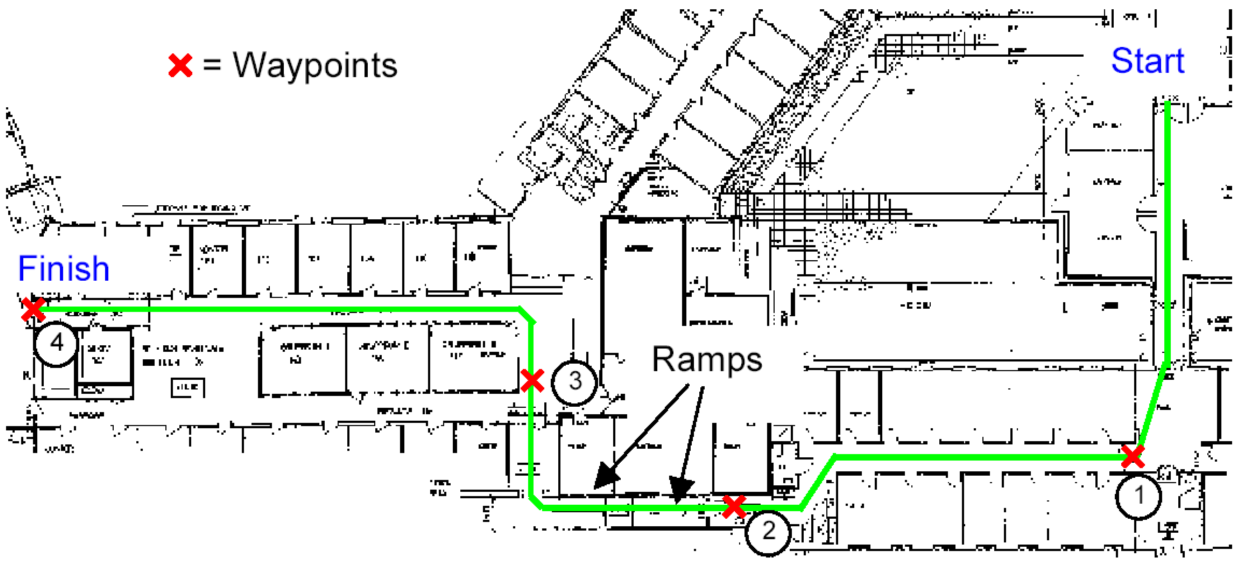


Figure 2.25 Waypoints in an indoor test (from [38]).

2.3.3 Map Matching

The navigation solution developed using electronic aids such as GPS can be enhanced when it is possible to assume that the person or object being located travels only along certain routes on a map; for example, it may be assumed that vehicles are always on paved streets. This *a priori* information can be used to "force" the estimated position to be on the nearest point on the possible routes. The constraints of indoor construction similarly can be used to refine estimates of the position of a person or object moving within a building—people and objects do not pass through walls, they pass along corridors and through doorways. Figure 2.26 illustrates the conversion of a building plan in the form of a CAD drawing into a simplified "graph" of possible positions in the building, modeled as a combination of "nodes" and "links."

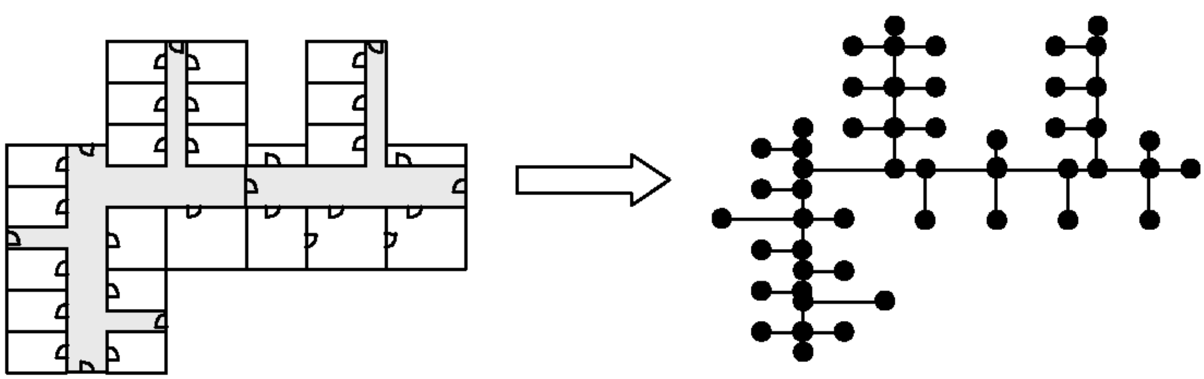


Figure 2.26 Transformation of a CAD model into a node/link model (from [39]).

3. Use of a DRM for Indoor Navigation

In this section we summarize tests exploring the use of a commercially available dead reckoning module (DRM) for indoor navigation. After describing the device's configuration and use, we provide details about the particular indoor scenario used for testing, including the establishment of known waypoint positions, then show example results of position tracking using the DRM with and without additional data processing. Based on these tests, we offer conclusions to guide further tests and applications.

3.1 Device Description

For our tests of indoor dead reckoning, we purchased a development kit for a gyro-stabilized DRM from Point Research Corporation, now a subsidiary of Honeywell. The items included in the development kit are pictured in Figure 3.1:

A. GyroDRM™ containing a GPS receiver with Li-ion battery in plastic housing with belt clip.
B. Software and user manuals on CD.
C. GPS active antenna.
D. RS-232 serial computer interface.
E. Event marker switch.
F. AC adapter.
G. Li-ion battery charging adapter.

3.1.1 Configuration and Use

Normally, in an outdoor application, the GPS receiver provides position fixes that are credible and that calibrate and correct the DRM's calculations of distances based on step counting. Occasionally there are lapses when the person carrying the DRM passes through a "shadow" area in which the GPS signal fades out, such as a forest or an urban canyon. During the temporary loss of GPS signal, the DRM maintains position by counting steps and measuring magnetic heading. The DRM uses Kalman filtering techniques to weigh the GPS and inertial measurements appropriately to produce an integrated estimate of position, direction of travel (heading), and length of stride. In our indoor application, instead of GPS fixes to calibrate and correct the DRM we use known waypoint positions that are manually detected and identified as a demonstration of the concept of using some other sensing method, such as RFID, to detect and identify the waypoints.

For the purposes of our indoor tests, the GPS antenna was not used since it was not possible to receive useful GPS signals inside the building.

The software included with the development kit included a program for initializing the DRM and for displaying the measurements in real time in terms of "x" and "y" displacements in meters from the original measurement position, defined as the origin. Initialization of the DRM

Figure 3.1 Development kit including DRM (from [36]).

position using the software can only be done using GPS coordinates; this GPS initialization enables the magnetic heading sensor to compensate for the variation in the direction of the Earth's magnetic field from place to place, and does not affect the x and y values.

3.1.2 Output Data

During a measurement period, the DRM outputs data as specified by commands sent to it using the software interface, and this data can be logged into a file for non-real time processing. For our test purposes, we suppressed the collection and logging of GPS information. After a measurement period, the log file can be imported by a spreadsheet application, such as Excel, then edited. The data fields initially available when the log file is imported are listed in Table 3.1, along with those added in order to simulate the reading of waypoint information.

Table 3.1 DRM log file data fields as imported by a spreadsheet and modified.

DRM data fields retained for post processing	DRM data fields edited out (discarded)	Data fields added for tracking studies
Time (HH:MM:SS) Step count (East, North) = (x, y) in meters Heading in degrees Stride (length of a step) in millimeters Mark event indicator/count	DRM altitude in meters Body orientation offset in degrees Coordinates from GPS receiver and estimated error Integrated GPS and DRM coordinates and estimated error Flag indicating new GPS fix	(x, y) values for the position at each Mark event

Theoretically, it would be possible to convert the waypoint positions into GPS coordinates and emulate an external GPS data source. This procedure would cause the DRM's internal Kalman filter to use the waypoint position corrections to modify its East and North position estimates. However, we did not use this methodology because we found out that waypoint positions with resolution below one meter require GPS coordinates with very high precision; such precision is not feasible because of the uncertainty in the Earth models on which the conversions are based. As described below, the DRM integrated position coordinates were discarded from the test data for our purposes, and new "integrated waypoint and DRM" positions (x and y) were developed using only the DRM measurements as inputs.

3.2 Test Scenario Description

In order to learn how well the DRM would work as a navigation device in an indoor environment, we conducted several tests in our office building, whose geographic position and orientation is shown above in Figure 2.9.

3.2.1 Waypoints for DRM Tests

After using the waypoint (x, y) values given in Figure 2.9 for a trial run, it became apparent that these position values, based on GPS information, are not sufficiently accurate. Therefore, a CAD drawing for the building was obtained and is shown in Figure 3.2. The North or y direction on this drawing is effectively rotated about 58.5 degrees clockwise from the drawing's vertical axis. Except for the positions numbered 13 and 14, which were selected later, the numbered (X, Y) waypoint positions shown in Figure 3.2 were converted to East (x) and North (y) positions by the straightforward formula for axis rotation:

$$x = X\cos\left(58.5^\circ\right) - Y\sin\left(58.5^\circ\right)$$
$$y = X\sin\left(58.5^\circ\right) + Y\cos\left(58.5^\circ\right)$$

The resulting waypoint (x, y) positions are listed in Table 3.2. The slight variations in distances between waypoints with similar geometry that are evident in Table 3.2 are due to the fact that the original (X, Y) points were determined manually using the CAD drawing.

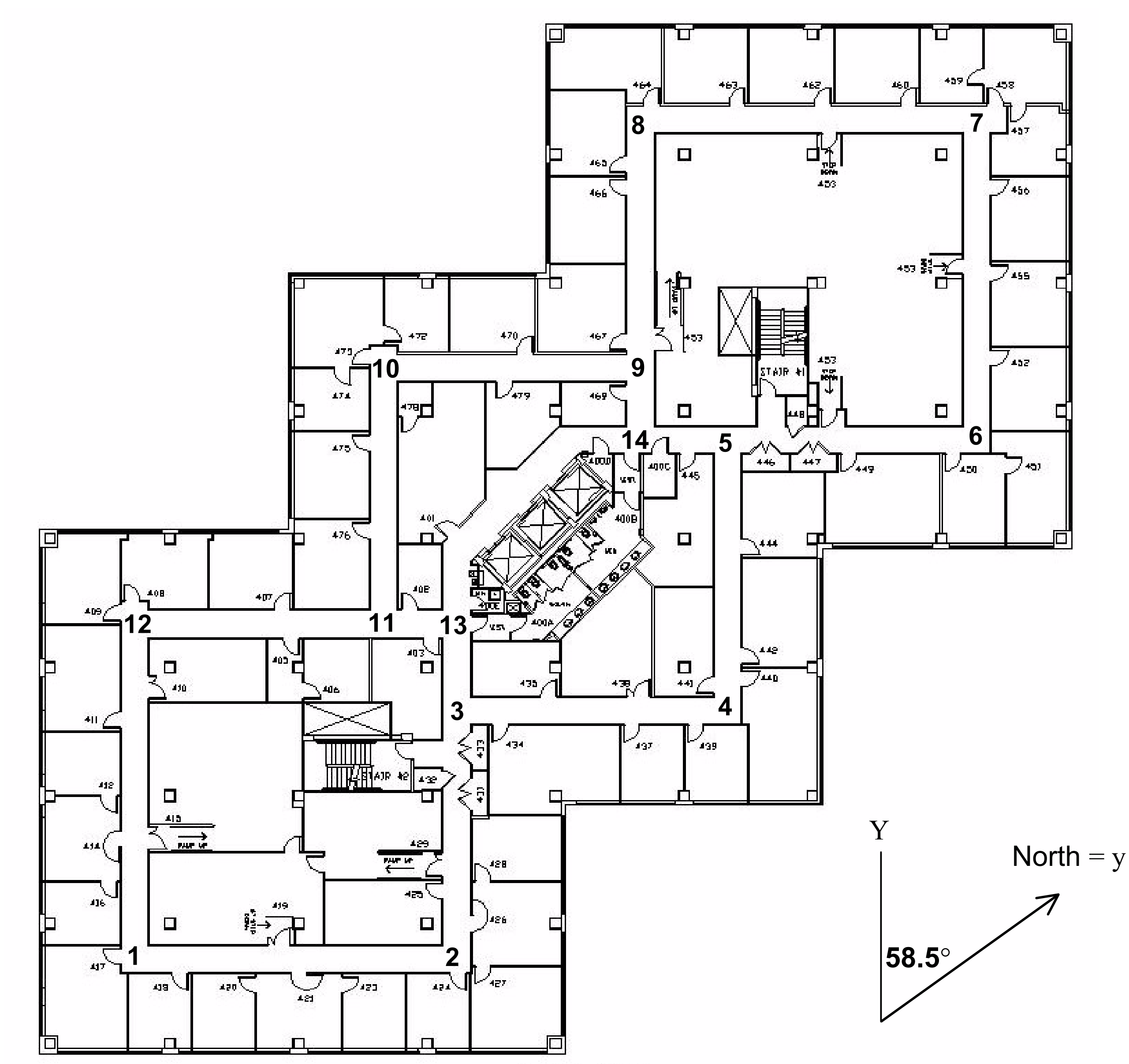


Figure 3.2 CAD drawing of building, with reference (waypoint) locations marked.

3.2.2 Trajectories for DRM Tests

Two different trajectories within the building were used for testing the indoor position tracking capabilities of the DRM. As sketched in Figure 3.3, the first trajectory was simply three trips around the outer perimeter of the hallways, and the second trajectory was a more involved path involving crossovers in order to observe the effect of a more complex set of direction changes on the magnetic sensor readings in view of certain magnetic anomalies observed on the first trajectory. For each trajectory, the starting position was the origin of the local coordinate system: point 1 in Table 3.2. Quantitative drawings of the trajectories are shown in Figure 3.4.

Table 3.2 Coordinates of building waypoint locations in Figure 3.2, in meters.

Ref. Point #	Position rel. building		Position rel. N, E	
	X	Y	x	y
1	0.00	0.00	0.00	0.00
2	18.23	0.0	9.52	15.55
3	18.23	14.01	–2.43	22.86
4	33.59	14.01	5.59	35.96
5	33.59	29.20	–7.36	43.89
6	47.66	29.20	–0.02	55.89
7	47.62	47.17	–15.40	65.29
8	28.50	47.17	–25.35	48.93
9	28.50	33.34	–13.55	41.70
10	14.04	33.34	–21.10	29.38
11	14.04	18.88	–8.77	21.83
12	0.00	18.88	–16.10	9.86
13	—	—	–6.58	25.41
14	—	—	–9.97	39.53

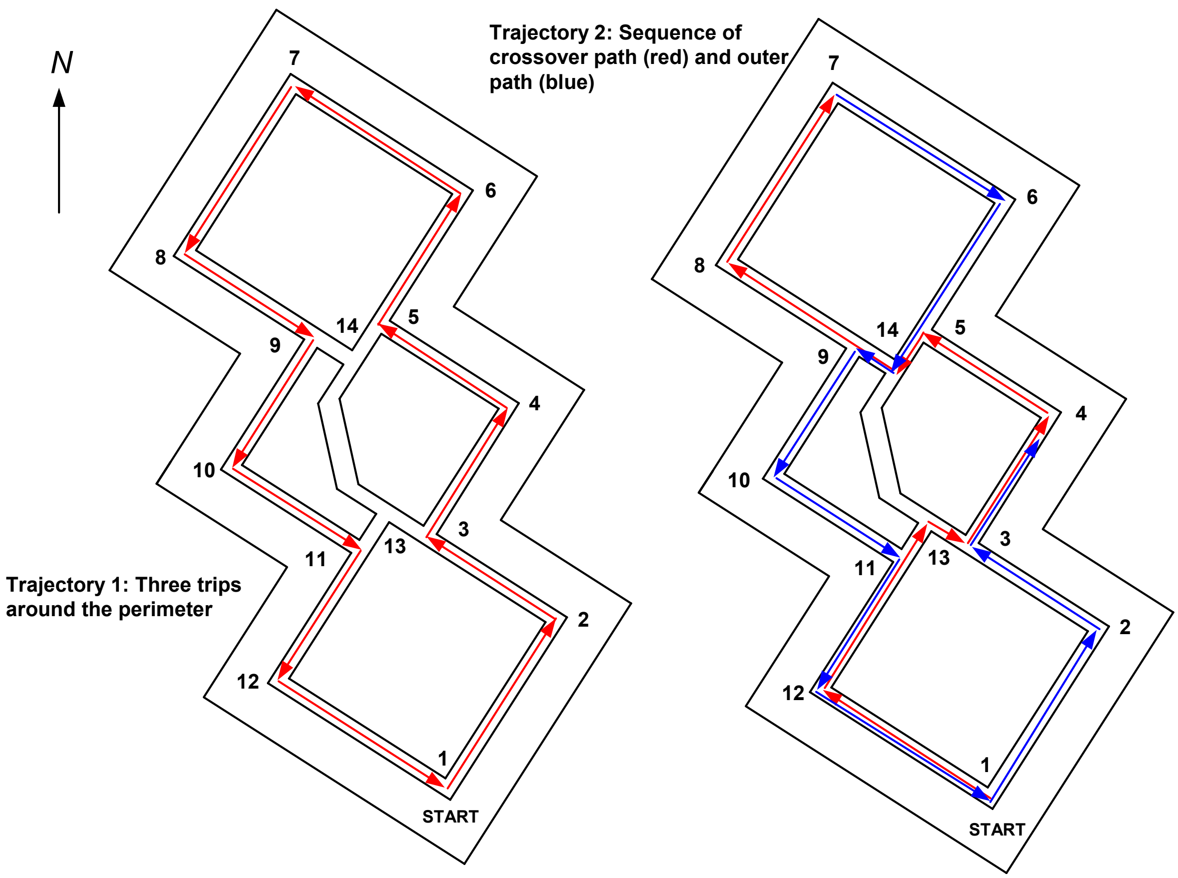


Figure 3.3 Trajectories used in indoor tests of DRM positioning.

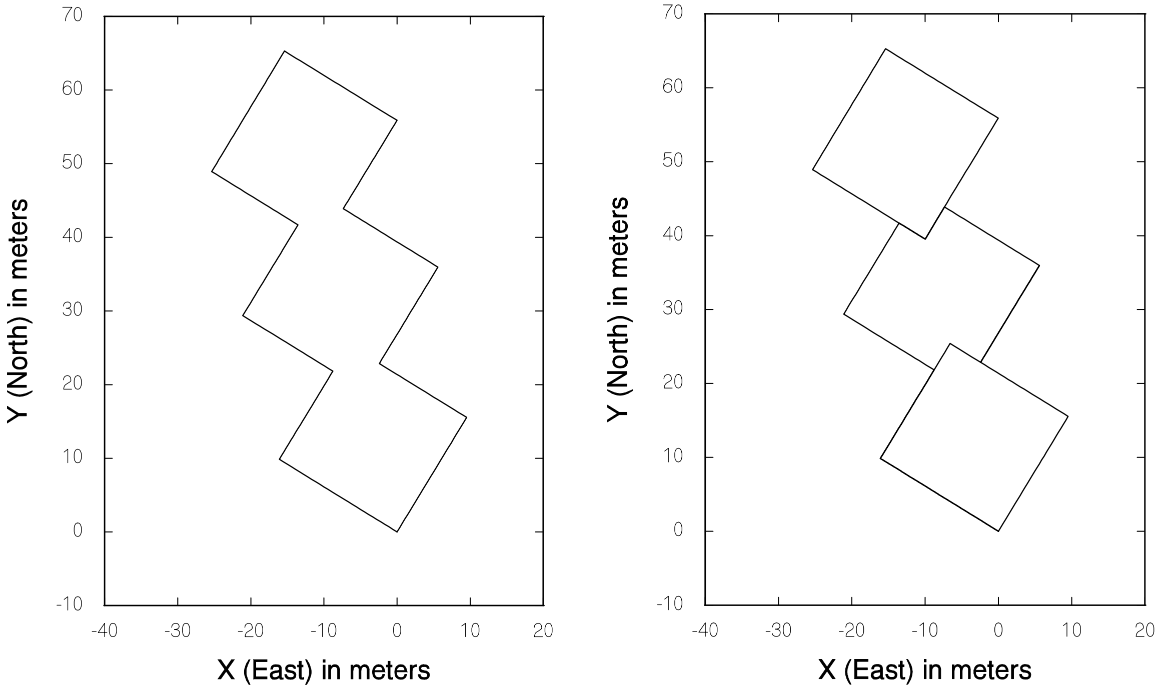


Figure 3.4 Quantitative representations of Trajectory 1 (left) and Trajectory 2.

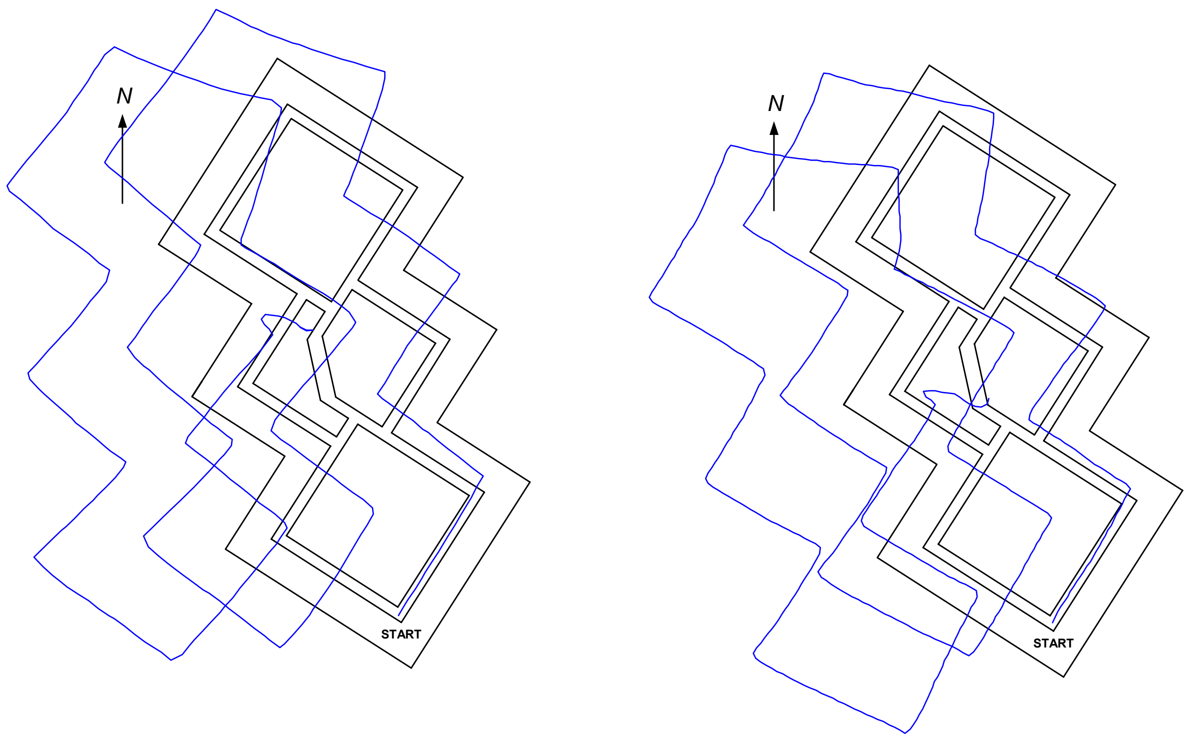
3.3 Indoor Positioning Results Using a DRM

In this section, we present the results of determining the position of person walking throughout the selected building scenario with the DRM output being logged onto a laptop carried by the person. Although the software on the laptop does produce a "quick look" display of the user's position, the data produced during the tests was collected for non-real-time analysis after the data collection. The event-marking switch supplied with the DRM was used to mark the point in the data log at which the person arrived at the known waypoint locations.

In what follows, we first show the results obtained using the DRM only. Then we show the results of "simple waypoint correction" in which the trajectory of (x, y) values developed by the DRM is simply corrected at each waypoint. Finally, we show the results of two kinds of adaptive filtering of the data provided by the DRM that can improve the accuracy of the real-time position estimate.

3.3.1 Results Using the DRM Output Only

Figure 3.5 shows the tracks developed by the DRM on two successive days for the Trajectory 1 path in the building. On the first track, displayed on the left side of Figure 3.5, the DRM used the 800-mm default value for the length of a step, called the "stride." It is evident from this track that the stride value was too large, since the distances between turns are consistently over-estimated. (In an outdoor application using GPS, the DRM itself would "learn" the correct value for the stride from the position corrections provided by the GPS receiver.) Another obvious



Using 800 mm stride value Using 750 mm stride value

Figure 3.5 DRM-only results for first trajectory.

feature of this track is that the heading provided by the magnetic sensor in the DRM is somehow thrown off in the part of the building corresponding to the top of the diagram, probably due to the presence of significant amounts of metal in the computer laboratory that is located in that part of the building.

On the second track a day later, displayed on the right side of Figure 3.5, a stride value of 750 mm was programmed into the DRM prior to the test. It is clearly seen that the more accurate value for stride results in a better track, at least initially, but the position solution is still not very accurate because the actual stride value varied for the person walking in the test, and the magnetic anomaly's effect on the heading causes the position estimate for each loop in the trajectory to get progressively less accurate.

To see if the direction in which the magnetic anomaly was approached would have any effect on the accuracy of the track, on a third day of testing we again walked around on the floor of the building but used Trajectory 2, which features crossovers and reversal of direction, along with a stride value of 750 mm. The DRM-only track resulting from this test is shown in Figure 3.6. On this track, the distances between turns are relatively accurate, but heading errors occurring from the start (different from those experienced on the first two days) caused the track to be quite inaccurate. However, the sensitivity of the DRM to changes in direction and its faithful reproduction of the many turns was impressive.

From the tracks shown in Figures 3.5 and 3.6, it is clear that the DRM, unaided by some external method of waypoint correction, cannot produce an accurate indoor track, mainly due to the magnetic effects of objects in the building.

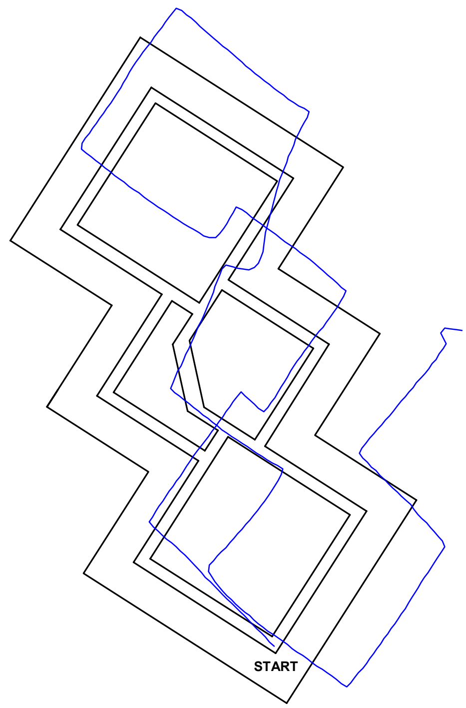


Figure 3.6 DRM-only results for second trajectory.

3.3.2 Results Using Simple Waypoint Correction

In order to simulate the effect of waypoint correction, the known East and North (x, y) positions in the building that are listed in Table 3.2 were used to correct the DRM-only position results. For example, in Figure 3.7 we show the DRM East (x) output and the X output obtained by adding or subtracting accumulated distance at each waypoint to make a correction.[4] In Figures 3.8 and 3.9, respectively, we show the corrected DRM tracks in two dimensions for Trajectory 1 and Trajectory 2.

For each leg of the track, the deviations of the magnetic heading and of the distance estimation based on counting steps are quite evident. While the quality of the distance estimation is rather predictable, given the value of stride that was assumed in each track, the occurrence of magnetic heading deviation is somewhat unpredictable.

With the rate of corrected used in the test, the estimated locations are almost acceptable, considering that they place the person carrying the DRM in or near the hallways as opposed to locations outside the building that were reported by the DRM without correction. In the next subsection, we explore some elementary filtering techniques that further improve the location estimates.

[4] The waypoint corrections were not perfect, since the point at which the mark button was pushed varied somewhat from the exact reference points.

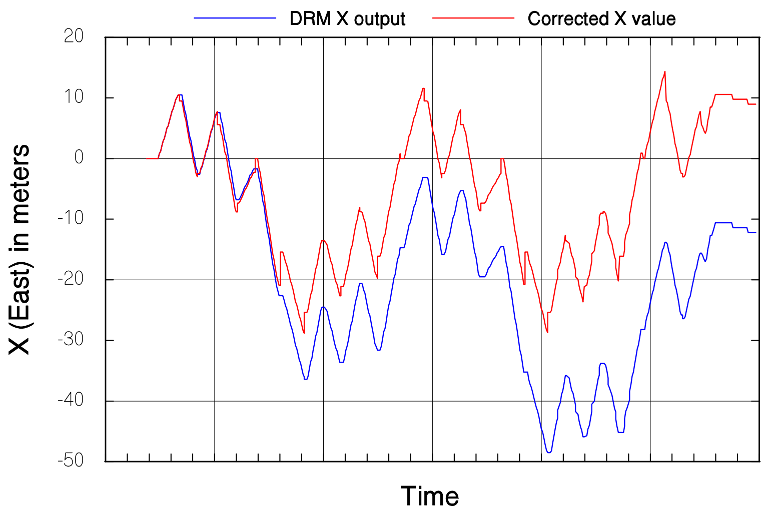


Figure 3.7 DRM X output and “corrected” X values.

Using 800 mm stride value

Using 750 mm stride value

Figure 3.8 Simple waypoint correction results for first trajectory.

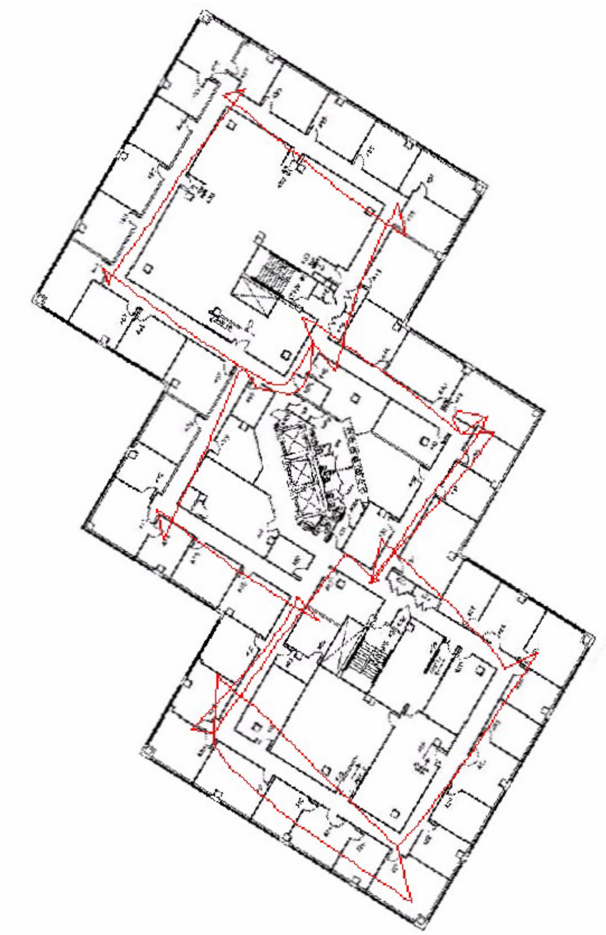


Figure 3.9 Simple waypoint correction results for second trajectory.

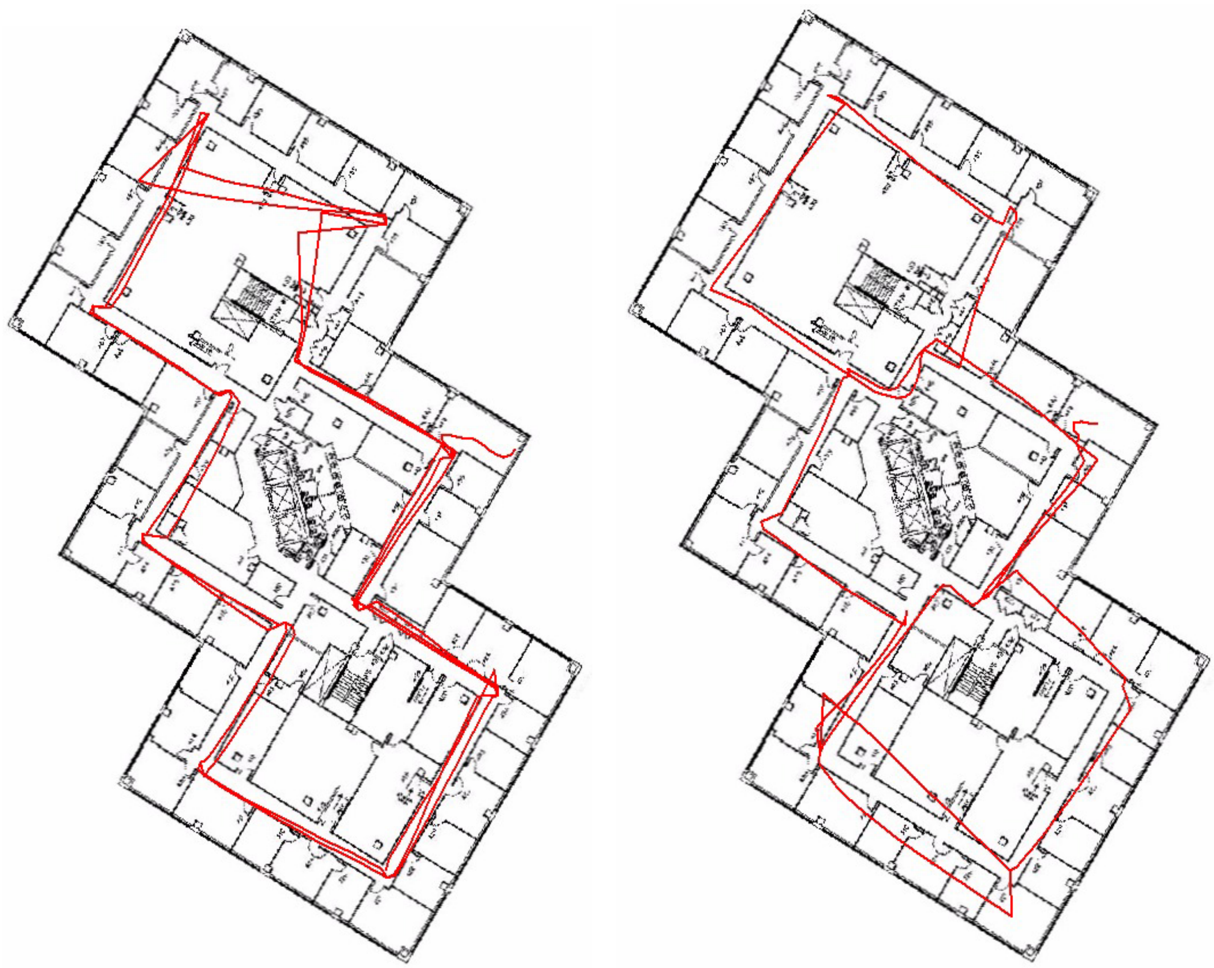
3.3.3 Results Using Adaptive Tracking

The measurements provided by the DRM (heading and step count) can be filtered to improve the location estimates. In what follows, we consider two filtering approaches: adaptive step size and adaptive heading correction.

3.3.3.1 Adaptive Step Size

In addition to adjusting the (x, y) position at each waypoint, we experimented with adapting the step size (stride) to a new fixed value at each waypoint. As mentioned previously, this type of adaptation is performed automatically by the DRM when it is used outdoors and is able to receive position updates from a GPS receiver. The procedure that we tested is very simple: at each waypoint, estimate the stride by taking the true distance and dividing it by the number of steps, then using the DRM's reported heading to calculate X and Y increments per step until the next waypoint. Strictly speaking, this calculation of step size applies to the portion of the track just completed, but as an experiment we use it to predict the distance covered in the next portion of the track.

The resulting tracks are shown in Figures 3.10 for Trajectory 1 and Trajectory 2 in the two cases in which the DRM was initialize with a stride value of 750 mm. Visually comparing these tracks with the previous ones in Figures 3.8 and 3.9, we observe that the "corners" in the adaptive-stride tracks are considerably "neater" because there is less distance error to correct at a waypoint, in general. The legs of the tracks that are subject to magnetic anomalies stand out even more, however.



Trajectory 1, 750 mm initially

Trajectory 2, 750 mm initially

Figure 3.10 Tracks using an adaptive step size and the DRM's heading output.

3.3.3.2 Adaptive Heading Correction

Just as it is possible to use the waypoints to calculate and adjust for the error in assumed step size, the amount of heading error between waypoints can be calculated. Referring to Figure 3.11, the heading error can be estimated by subtracting the correct heading (the heading determined by the current waypoint and the previous waypoint) from the average measured heading (the heading determined by the track position before waypoint correction and the previous waypoint).

The geometry in Figure 3.11 assumes that the actual trajectory is straight between the two waypoints, but it may not actually be straight (as in parts of Trajectory 2). For that reason, the application of this calculated heading error to any correction of "future" measurements should be either "modest"—hedging against a change in the magnetic anomaly that is causing the error—or it should be "intelligent"—use some means to determine whether the path between waypoints has been straight.

In order to evaluate the potential effectiveness of adaptive heading correction of this type, we further modified the post-processing of the DRM data for the Trajectory 2 scenario to include a heading correction that is applied to the track estimation points that *follow* the calculation of the heading. Example results for Trajectory 2 are shown in Figure 3.12, in which it is evident in this case that applying the full correction was beneficial where the assumed track model was correct, but made the estimated track worse for the segments of the track following the crossover portions of the trajectory (compare with Figure 3.10). From Figure 3.12 we observe that the application of half the heading error correction avoided making the track worse after the crossovers, but did not do as good a job of correcting the heading error otherwise. These results suggest that a more sophisticated tracking filter could be successful in mitigating the effects of the magnetic anomalies that are founding in indoor scenarios.

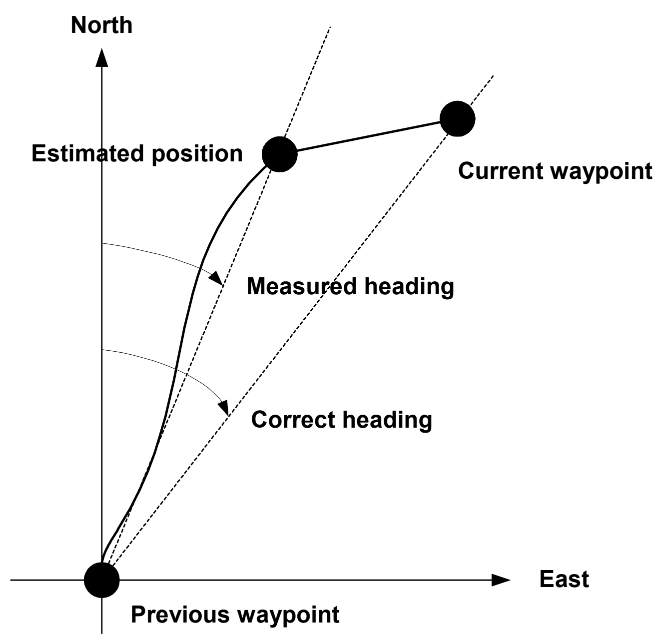


Figure 3.11 Heading correction geometry.

With full heading correction   With half heading correction

Figure 3.11 Tracks using adaptive step size and adaptive heading correction.

3.3.4 Summary of Tracking Results and Errors

Direct graphical comparisons are made of the various tracks for Trajectory 1 in Figure 3.12 and for Trajectory 2 in Figure 3.13, both in the case of a 750-mm initial value for the stride. The tracks included in these figures are

- The DRM output for East (x) and North (y) in meters
- The nominal track taken during the test, which was followed by the person walking to an accuracy of less than one meter
- The track resulting from simple waypoint correction of the DRM output
- The track resulting from simple waypoint correction plus adaptive step size processing.

Reduction of the graphical results to tracking error vs. time is given in Figures 3.14 and 3.15.

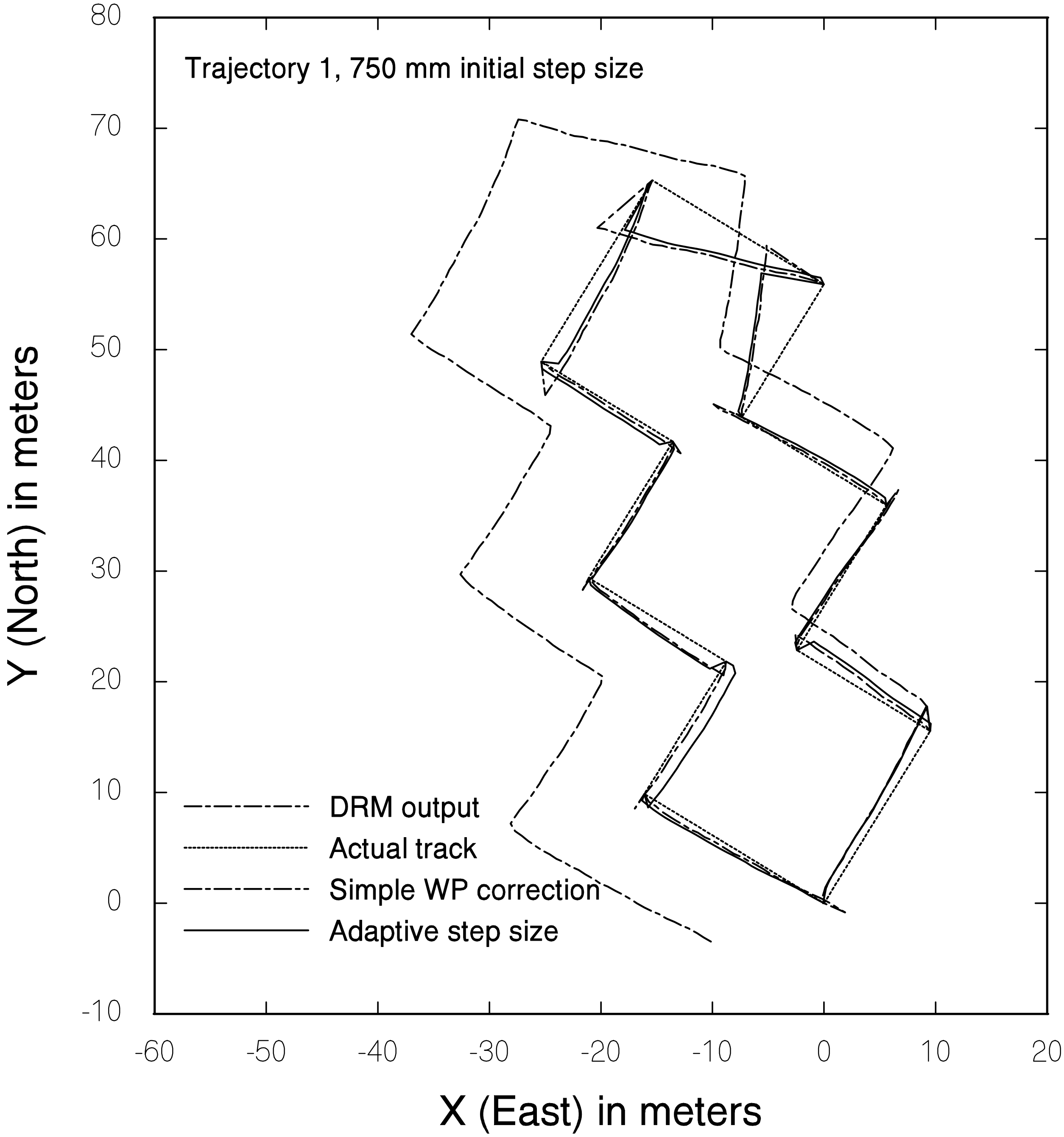


Figure 3.12 Summary of tracking results for Trajectory 1.

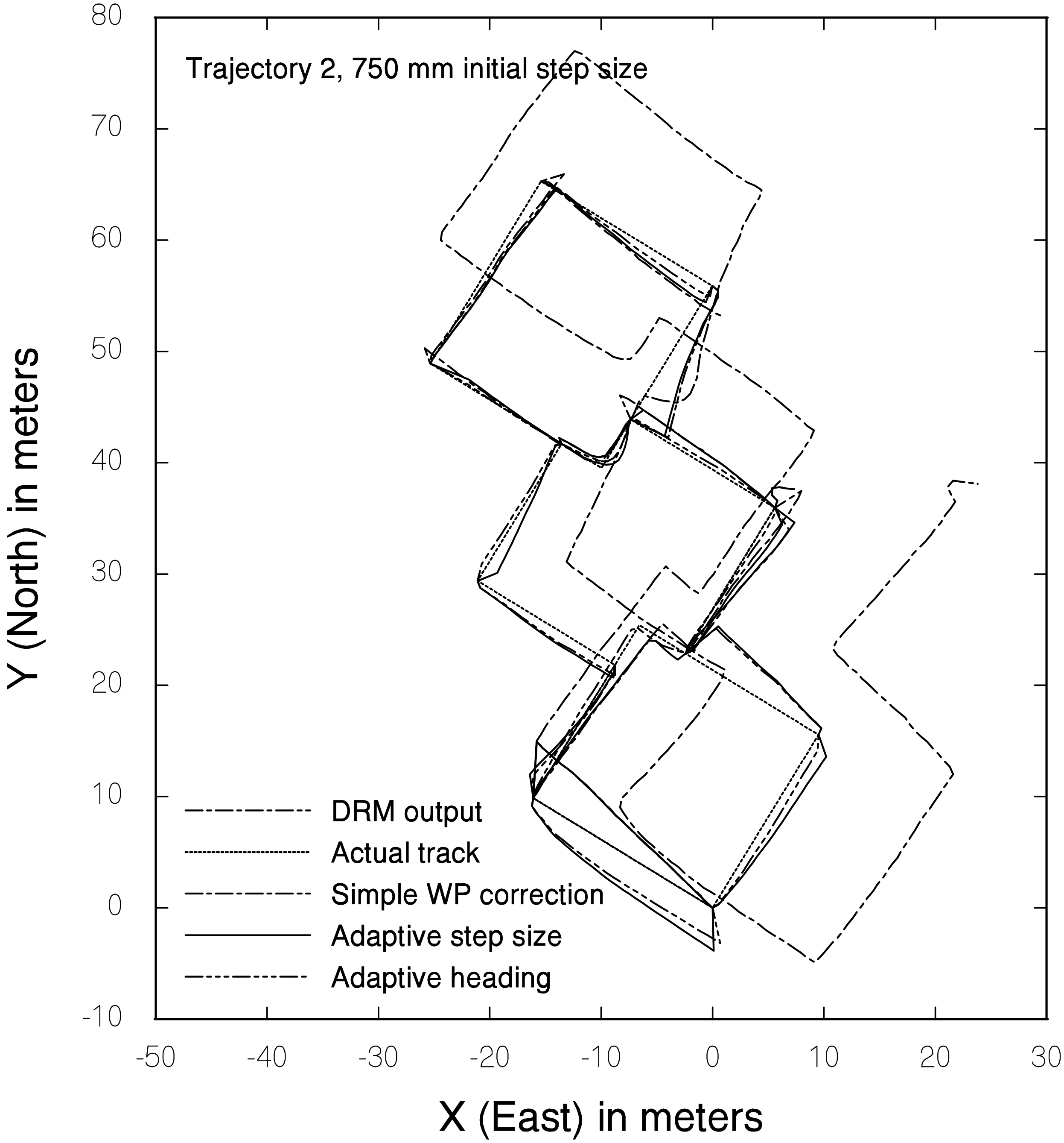


Figure 3.13 Summary of tracking results for Trajectory 2.

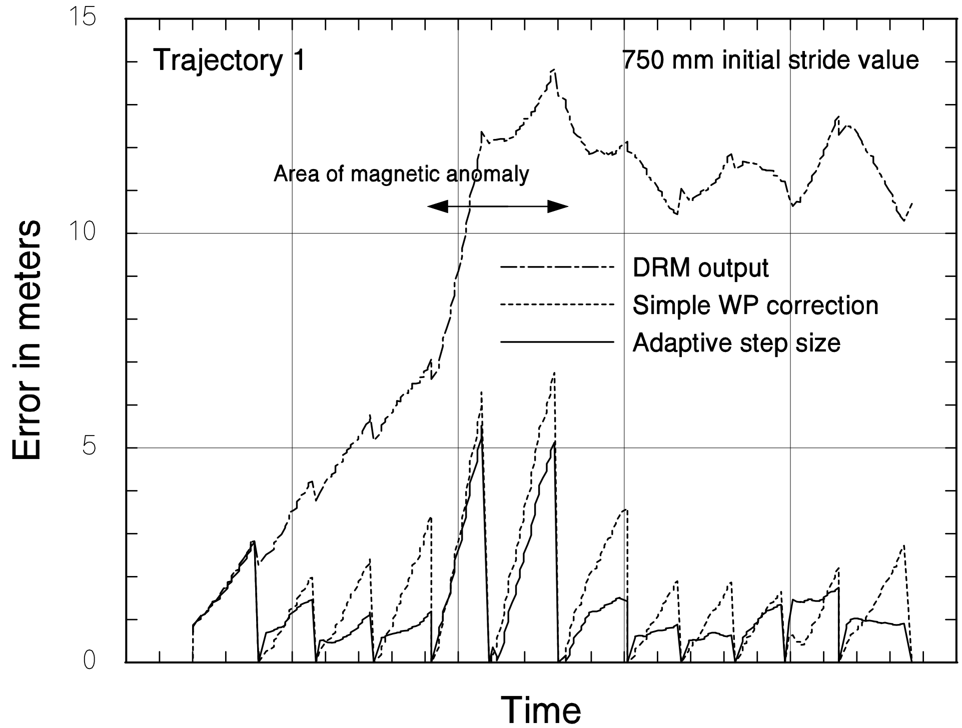


Figure 3.14 Tracking error for Trajectory 1 tests.

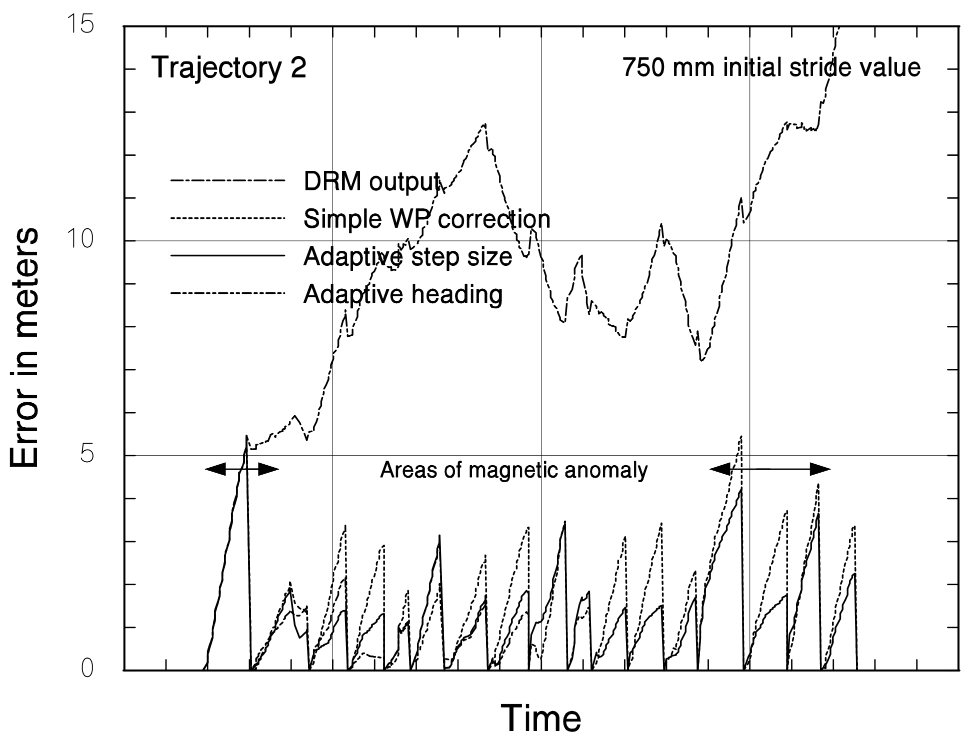


Figure 3.15 Tracking error for Trajectory 2 tests.

The average distance between successive waypoints in the scenarios we tested was about 15 meters for Trajectory 1 and about 14 meters for Trajectory 2. Looking at the "simple WP correction" results in Figures 3.14 and 3.15, the unfiltered DRM output's track error grew approximately linearly with time and thus approximately linearly with distance, giving a "sawtooth" appearance.

The maximum errors for each "tooth" in Figure 3.14 are given in Table 3.3, along with the overall maximum error expressed as the average percentage of distance, with and without the larger-error segments of the track that are due to magnetic anomalies. The table shows that adaptive step size processing (which the DRM unit can accomplish outdoors with GPS fixes) when added to waypoint correction reduces the raw maximum error from about 20% of distance to about 13% of distance; excluding the larger magnetic anomalies (indicated in the table by an asterisk), the reduction is from about 16% of distance to about 9% of distance. The average error for a "tooth" is about half the maximum, which gives an average error without magnetic anomalies and with adaptive step size that is compatible with the DRM specification of 1% to 5% of distance traveled, in its intended application [30].

The maximum errors for each "tooth" in Figure 3.15 are given in Table 3.4, along with the overall maximum error expressed as the average percentage of distance, with and without the larger-error segments of the track that are due to magnetic anomalies. The table shows that adaptive heading correction processing (which the DRM unit can accomplish outdoors with GPS fixes) when added to waypoint and step size correction reduces the raw maximum error from about 21% of distance to about 13% of distance; excluding the larger magnetic anomalies, the reduction is from about 20% of distance to about 11% of distance. The average error for a "tooth" is about half the maximum, which gives an average error without magnetic anomalies and with adaptive heading and step size correction that is compatible with the DRM specification of 1% to 5% of distance traveled.

Table 3.3 Errors before waypoint corrections for Trajectory 1, 750 mm stride.

Approximate distance between corrections	Error before simple WP correction	Error for adaptive step size before corr.
18 m	2.83 m	2.80 m
14 m	1.97 m	1.46 m
14 m	2.41 m	1.17 m
14 m	3.41 m	1.19 m
14 m	6.30 m*	5.52 m*
18 m	6.75 m*	5.13 m*
18 m	3.58 m	1.42 m
14 m	1.90 m	0.89 m
14 m	1.87 m	0.63 m
14 m	1.65 m	1.34 m
14 m	2.20 m	1.75 m
18 m	2.72 m	0.91 m
Average percentage of distance	20.3%	13.1%
Average excluding (*) entries	16.1%	8.9%

Table 3.4 Errors before waypoint corrections for Trajectory 2, 750 mm stride.

Approximate distance between corrections	Error before simple WP correction	Error for adaptive step size before correction	Error for adaptive heading before correction
18 m	5.5 m*	5.4 m*	5.4 m*
22 m[5]	1.42 m	0.94 m	1.50 m
14 m	3.38 m	1.38 m	2.16 m
14 m	2.91 m	1.32 m	0.28 m
8 m	1.85 m	1.13 m	1.13 m
14 m	2.02 m	3.15 m	3.09 m
18 m	2.68 m	1.75 m	1.62 m
18 m	3.33 m	1.79 m	1.29 m
14 m	3.47 m*	3.42 m*	3.73 m*
8 m	1.47 m	1.84 m	1.18 m
14 m	3.12 m	1.46 m	1.01 m
14 m	3.43 m	1.51 m	1.34 m
14 m	2.33 m	1.69 m	1.42 m
18 m	5.46 m*	4.22 m*	3.67 m*
18 m	3.72 m	1.76 m	0.93 m
14 m	4.36 m	3.66 m	3.40 m
14 m	3.37 m	2.26 m	0.64 m
Average percentage of distance	21.5%	15.7%	13.5 %
Average excluding (*) entries	20.0%	13.4%	10.8%

3.4 Conclusions and Ideas for Further Study

In this subsection we conclude this phase of the study of indoor navigation for possible first responder localization and, in particular, the use of a DRM with waypoint corrections. We also record for reference our ideas for further study based on the results so far.

3.4.1 Conclusions

The following conclusions may be drawn from the results of this study:

- The DRM that we tested shows that dead reckoning using magnetic headings definitely can be made useful for tracking first responder personnel indoors, provided that some form of waypoint correction can be implemented.

[5] The arrival at the first waypoint (reference point 11) was inadvertently not marked during the test.

- The drift of the DRM in the indoor tests we conducted indicate that the position developed by the DRM, with waypoint correction, drifts away from the actual track by about 10% to 20% of distance, depending on the strength and number of magnetic anomalies in the building that distort the local magnetic field.
- It follows that a one-meter maximum deviation from track can be obtained by placing waypoints about 5 to 10 meters apart, and a one-meter average deviation can be obtained by placing waypoints about 10 to 20 meters apart. In buildings with known magnetic anomalies, the selection of waypoints can be made to counter the effects of these anomalies.
- The stabilization of the magnetic heading measurement by means of the included gyro device significantly enhances the performance of the DRM we tested. The enhancement can be seen by comparing Figure 3.16, below, with Figure 3.8: the smaller local variations are averaged out or ignored with the aid of the gyro. However, the settling time of the gyro may be too long for indoor applications, causing heading drift from a strong, long-lasting magnetic anomaly to be continued over the next part of the track.

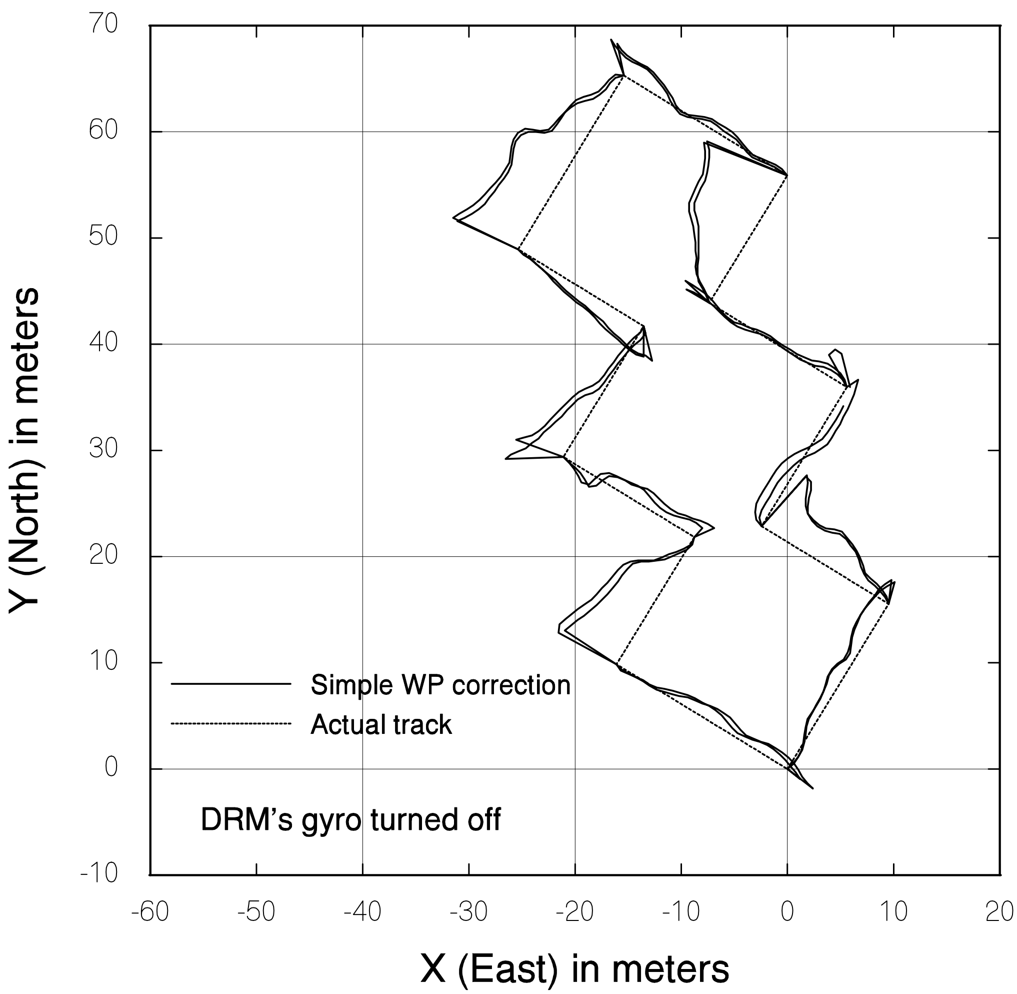


Figure 3.16 Waypoint-corrected DRM track with gyro turned off.

- Adaptive tracking of the walking person's step size (stride), based on waypoint corrections and step counting, dramatically reduces the DRM's maximum indoor track error from 15% to 20% of distance between waypoints with simple waypoint correction to 10% to 15% of distance between waypoints. This result holds for the relatively steady walking done during the tests.
- Waypoint corrections can also be used to detect the DRM's indoor heading errors that happen because of magnetic anomalies. We showed by example that it is possible to perform adaptive heading correction to improve the accuracy of the track developed by the DRM.

3.4.2 Ideas for Further Study

The results of this study stimulate the following ideas for further study:

- The walking patterns of first responders often are irregular, plus they may crawl or fall down. The data observable from the output of the DRM can be processed to detect irregularities in order to implement a "smart" way of correcting the DRM's estimate of distance traveled based on counting steps.
- Magnetic anomalies may be different in nature for different structures. Further tests in different buildings are needed to assess the degree of this effect.
- Correction of heading measurements based on waypoints also needs to be "smart" by determining when and how much of the detected heading error should be applied to future measurements. The DRM we tested has an option to report its own detection of magnetic anomalies; further study is needed to see if this feature can be used to correct heading estimates. Alternatively, the DRM could be operated in the "gyro off" mode and filtering performed on the raw magnetic heading output to detect and adaptively correct for anomalies. Yet another idea is that, if waypoints have been installed in a particular building in the form of RFID tags whose identities are associated with locations,[6] then it may be possible to associate magnetic anomaly information with individual tags as well.
- We have not so far investigated the accuracy or stability of the altitude measurement produced by the DRM.
- Just as RF field strengths have been used successfully to provide "maps" for indoor localization, we may be able to use the DRM's magnetometer output to associate magnetic field strength values and/or patterns with locations in a building.

In addition, we are interested in obtaining and testing an INU in the same way that we have tested the DRM.

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[6] In an advanced concept of this project, the RFID tags could contain the actual location information on them, eliminating the need to look up this information or to "pull" it from somewhere.

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