



KTH Architecture and
the Built Environment

Infrastructure for navigation in urban and indoor areas – feasibility study

Milan Horemuž

Research project supported by Stiftelsen J Gust Richert

Stockholm, August 2009

Royal Institute of Technology

Department of Transport and Economics

Division of Geodesy

Table of Contents

1	Introduction.....	4
1.1	Background and motivation.....	4
1.2	Objectives	5
2	Navigation: principles, terms and definitions	7
2.1	Navigation.....	7
2.2	Reference system	8
2.3	Concepts of trajectory determination.....	10
2.3.1	Signpost systems	10
2.3.2	Wave based systems.....	11
2.3.3	Dead reckoning systems.....	12
2.3.4	Comparison of navigation systems.....	12
3	Overview of navigation systems	14
3.1	Global navigation satellite systems (GNSS).....	14
3.2	Terrestrial radio navigation systems for aviation and maritime use.....	19
3.2.1	Point source systems	19
3.2.2	Area-based systems	21
3.3	Cellular communication networks.....	23
3.4	The Active Badge Location System	26
3.5	Active bat.....	29
3.6	Cricket.....	31
3.7	RFID Location Systems.....	32
3.8	WLAN and Bluetooth based location systems	35
3.9	Inertial navigation system.....	37
4	Conclusions	41
5	References	44

1 Introduction

1.1 Background and motivation

The use of GIS (Geographic Information Systems) and positioning services has been rapidly growing during the recent years. The main reason for this trend is the availability of small and cheap GPS (Global Positioning Service) navigators, which today are available not only to military and professional users, but also to private persons. Location awareness is important not only for way finding but also for other purposes, as tracking of cars, people or animals, for location based services and for social mobile applications (friend finder, location sharing – inform people where you are). With the development of complex buildings and structures inevitably arises the question of indoor personal navigation. Guiding the customer in a shopping centre, directing the visitor in the hospital or evacuating a worker out of a dangerous area; these are just few examples of indoor personal navigation problematic.

GPS navigator is commonly associated with a device that can show digital maps connected to a database of different kind of objects (restaurants, fuel stations etc.) But in fact, this device consists of at least two independent components:

- GPS sensor that provides actual position and velocity of the user and
- GIS that provides all other functionalities that we expect from a “GPS navigator”, like to show our position on the map, compute routes, find restaurants and so on.

It is obvious that the GPS sensor can be replaced by any other positioning device, without affecting the functionality of the GIS component.

GPS receiver determines its 3D position by tracking signal from at least four GPS satellites. It means that the receiver must “see” sufficiently large part of the sky. The signals passing through buildings or other obstacles get weaker and therefore rather unusable for navigation. That is why GPS navigation does not work well in cities, tunnels or indoor environment. To be able to navigate in such environments other methods and sensors must be used.

Navigation methods can be divided into two groups: autonomous and non-autonomous. Autonomous methods do not rely on any man-made infrastructure, i.e. they do not need any special reference objects or signals. Typical example of an autonomous technique is inertial navigation, where accelerometers sense the acceleration (or the change in velocity) and gyroscopes measure the rotation rate, i.e. the change in orientation. By integrating of these quantities we can compute the change of the initially known position and orientation.

The non-autonomous techniques use some kind of infrastructure (artificial objects or signals) as reference for positioning. An example of such technique is GPS, where the GPS satellites are used as reference points with known coordinates. In most cases, the autonomous techniques deliver only change of the position, so the initial position must be known. Non-autonomous techniques provide position in some well-defined global (or national) reference system; for example GPS provides position in reference system WGS84 (World Geodetic System 84).

For most of the navigation applications and position-related services, it is essential to determine the “absolute” coordinates, i.e. the position expressed in a global reference system. It means that an infrastructure supporting the non-autonomous navigation must be established. This “infrastructure” can be network of active or passive reference objects with known coordinates. An example of an active reference object is pseudolite – device that transmits GPS-like signal. A set of pseudolites installed in an industry hall enable the usage of GPS receivers for indoor navigation. Passive reference object can be any well-visible object (target) with known coordinates, for example church tower, special targets attached to the walls of buildings etc.

Nowadays there are many types of systems for indoor navigation available on the market. Most of them are specialised for a certain type of application and they are using special reference objects. Our vision is that a modern city should have some kind of standard infrastructure supporting non-autonomous navigation. Such infrastructure would consist of a network of reference objects and eventual communication links between users and the system. This would be a base for variety of position-based services as well as great help for handicapped people and emergency services. The navigation system based on this infrastructure should help to find not only addresses, but also rooms or places within buildings.

1.2 Objectives

The main goal of our research is to analyse navigation techniques suitable for *city navigation*, i.e. personal navigation in urban and indoor areas. Each navigation technique will be assessed based on the quality, required infrastructure, instrumentation and costs. The quality of the investigated systems will be assessed using the following parameters (Hofmann-Wellenhof et. al. 2003):

- **Accuracy** defined as the degree of conformance between measured and true position. We can distinguish: i) *predictable* (or absolute) accuracy, which is the accuracy of a position solution of a navigation system with respect to the true position, ii) *repeatable* accuracy (precision), which denotes the accuracy with which

a user can return to a position whose coordinates have been determined at a previous time with the same navigation system, iii) *relative* accuracy is the accuracy with which a user can determine a position relative to the position of another user of the same navigation system at the same time. Relative accuracy is highly relevant for collision avoidance, while absolute accuracy is the most important for city navigation. Therefore in this report the term accuracy will refer to absolute accuracy. In this report we define three levels of accuracy:

- *High accuracy*: the positional error is on metre level
 - *Medium accuracy*: the positional error is on tens of metres level
 - *Low accuracy*: the positional error is on hundreds of metres level
- **Availability** is defined as the percentage of time that the services of the system are usable. It is an indication of the ability of the system to provide a usable service within the specified coverage area. Signal availability is the percentage of time that the signals transmitted from external sources are available for use. Availability is a function of both the physical characteristics of the environment and the technical capabilities of the transmitter facilities.
 - **Capacity** is the number of users, which can use a navigation system simultaneously.
 - **Continuity** is the ability of a system to perform a function without interruption during an intended operation. More specifically, continuity is the probability that the specified system performance will be maintained for the duration of a phase of operation, presuming that the system was available at the beginning of that phase of operation.
 - **Coverage** of a navigation system is that surface area or space volume where the performance of the system is adequate to permit the user to determine a position to a specified level of accuracy.
 - **Dimension** defines whether a navigation system provides one-, two-, or three-dimensional positioning. Some systems have the ability to derive also the fourth dimension, i.e., time.
 - **Integrity** is the ability of a navigation system to provide timely warnings to the users when the system should not be used. Integrity involves several sub-parameters such as the time to alarm, the alarm limit (reflecting the maximum tolerable error of the system), or the maximum alarm frequency.
 - **Reliability** describes the probability of performing a specified function without failure under given conditions for a specified period of time.
 - **Update rate** (or fix rate) is defined by the number of independent position solutions (or fixes) per time unit.

2 Navigation: principles, terms and definitions

2.1 Navigation

The word "navigation" originates from Latin and is derived from the words "navis", meaning "ship", (or "navigare" meaning "to sail") and "agere", meaning "to act" or "to drive" (dictionary.com). From Latin meaning we can see that the term navigation was originally describing the act of guiding the ship from one place to another. Today we are using the term navigation in connection with all kind of travels (air, land, space) and even in connection with "mind travels" (navigation on internet). More technically, the navigation is **trajectory** determination and **guidance**. *Trajectory* determination relates to the derivation of the **state vector** of an object at any given time. Typically, the state vector includes position, velocity, and attitude. Knowing the state vector, we can answer the questions like "where am I?", "what is my speed?" and "where am I heading?". Guidance is the act of guiding a **platform** (vehicle, object or person) along the predefined **route** and it addresses questions like "where to go?" and "how to go?" The term **trajectory** describes a polygon connecting subsequent positions of a vehicle, i.e. it is actual travelled path. The **route** is a detailed list of manoeuvres to be performed by the vehicle to reach a destination.

The navigation is closely related to geodetic surveying. Traditionally, surveying is characterized by a high-positioning accuracy, static observations, and post-processing of the observed data. In contrast, the navigation usually utilises positioning devices and methods with a lower accuracy, but the kinematic observations are processed in real time. Real time processing means that the state vector is available directly, or with very short delay, after the measurement. As the sensors and instruments become more precise and smaller, the differences between surveying and navigation are gradually vanishing.

All components of the state vector are relative quantities. Position, velocity and attitude of an object can be expressed only in relation to some reference objects. For all types of navigation techniques, it is inevitable to establish some kind of **infrastructure**. The word infrastructure comes from Latin words *infra* and *structure*. *Infra* means "below" and *structure* is past participle of *struere*, which means "to put together". According to dictionary.com, infrastructure is an underlying base or foundation especially for an organization or system, the basic facilities, services, and installations needed for the functioning of a community or society, such as transportation and communications systems, water and power lines, and public institutions including schools, post offices, and prisons. In our report the term **infrastructure for navigation** includes all installations, reference objects, communication facilities and databases that are required for navigation.

2.2 Reference system

The **position** is one of the keywords in navigation; it is given by a set of coordinates related to a well-defined **reference frame**. The process of obtaining a position is called position determination, or shortly positioning. There is a term with similar meaning, also often used in navigation: **location**. Location describes a position in terms of topological relations, for example “near the lake”, or “close to the statue of Liberty”. The advantage of the position expressed in terms of coordinates is the uniqueness. On the other hand, the coordinates are not as understandable for human as the topological description, which is often non-unique (there are many lakes; there can be many statues of liberty). The state vector (i.e. position, velocity and attitude) determined by a navigation system is expressed in certain frame of reference. The reference frame is defined as a set of reference objects (points) with known coordinates computed in certain **reference system**. A reference system defines the position of origin, the orientation of coordinate axes and also methods (including the numerical values of constants) for the computation of coordinates. The distinction between the terms reference system and reference frame was introduced in Moritz and Mueller (1987). Detailed information about reference systems can be found in many geodetic and GPS textbooks, for example Leick (2004), or in the web page of International Earth Rotation Service (IERS) <http://www.iers.org>. IERS is the organisation that defines and maintains international celestial and terrestrial reference systems (ICRS, ITRS).

The reference systems can be divided into two groups: **celestial** and **terrestrial**. The main difference between them is the orientation of the reference axes. The axes of a **celestial reference system** are fixed with respect to the distant stars; usually z-axis is parallel with the rotation axis of the Earth and x-axis points towards Vernal equinox. Vernal equinox is an intersection between terrestrial equatorial plane and the virtual path of the Sun between stars as seen from the Earth. The origin of the celestial systems is placed either to the centre of gravity of the Earth or to the centre of gravity of the Solar system. In this way, an inertial or non-rotating system can be realised. Such systems are suitable for navigation in space, but rather inconvenient for navigation on the Earth’s surface, since the coordinates of static objects are changing in time due to the Earth’s rotation.

The axes of **terrestrial reference systems** are fixed to the Earth’s body. For the systems with global coverage, z-axis coincides with mean rotation axis of the Earth and x-axis points towards the intersection of Greenwich meridian and the equator and the origin is placed into the Earth’s centre of gravity. For applications, where the navigation area is small, a local reference system might be suitable. Any suitable object or point in the area of interest can be chosen as the origin of a local system. The axes are oriented along the natural directions, like north, east, up, or along the walls of the building or room. The above mentioned coordinate axes form 3D Cartesian coordinate system, i.e. all three axes are mutually perpendicular. Generally, none of these three axes points “up”, so to be able to express the height, we have to define a reference surface, which preferably matches

(approximates) the surface of the Earth. The figure of rotational ellipsoid (2-axes ellipsoid) is commonly used as geometrical figure of the Earth. The ellipsoid fits the figure of the whole Earth just approximately; better fit can be achieved if we fit the ellipsoid just to smaller territory. Such *local ellipsoid* fits well the given territory, but does not fit other parts of the world. The ellipsoid is suitable figure for mapping purposes, but it is not a good reference surface for heights. Naturally, we would expect that water should flow from higher to lower point; but it is not necessarily so, if we measure heights relative to ellipsoidal surface, since this surface is not parallel with equipotential surface. The equipotential surface is a surface with equal gravitational potential and it is formed by undisturbed water surface. The equipotential surface that coincides with mean sea level is chosen as the reference surface for height measurements and it is called *geoid*. The height related to the geoid, usually denoted by H , is referred as height over mean sea level (MSL), normal or orthometric height. In many GPS and GIS software, the height over geoid is denoted as *elevation* and height over ellipsoid as *height*.

For the needs of city navigation, mainly the global terrestrial systems are of interest. For example, Global Positioning System (GPS) uses World Geodetic System 1984 (*WGS84*) as working reference system. Russian GLONASS uses a similar reference system denoted as *PZ-90*. Beside these reference systems used primarily by Global Navigation Satellite Systems (GNSS), there are also national and regional reference systems used in particular country or region. As an example we can mention *SWEREF99*, which is national reference system in Sweden, or system *RT90*, whose variations are used by different municipalities in Sweden. The differences between these systems are relatively small deviations in the computation of origin and the direction of coordinate axes. The result of these deviations is difference between the coordinates expressed in different systems. These differences can be on cm – dm level (*WGS84*, *ITRS*, *SWEREF*) but also on metre to hundreds of metres level (*WGS84*, *PZ-90*, *RT90*). Therefore it is very important to declare the reference system when providing numerical values of coordinates. For example, if position of an object given in *RT90* coordinates is displayed on a map drawn in *WGS84*, the positional error may be in level of 100 - 200 m.

Sometimes in literature the reference system is incorrectly referred as ***coordinate system***. Coordinate system is a system for assigning unique pair or triple of scalars (numbers) to any point in 2-dimensional (2D) or 3-dimensional (3D) space. These scalars are called coordinates and they uniquely define the position of the given point. The most common type of coordinate system is probably Cartesian system, defined by two or three mutually perpendicular axes. The coordinates are oriented distances between the point and the coordinate axes in 2D or coordinate planes in 3D. Another, frequently used coordinate system is ellipsoidal system, where the position of a point is given in form of latitude φ , longitude λ and height above reference ellipsoid h .

Reference system usually includes also a definition of **cartographic projection**, which is a way of projecting curved surface of the Earth into a planar surface of map. Cartographic projection is actually set of equations transforming ellipsoidal coordinate system into 2D Cartesian system. For more details see e.g. Grafarend and Krumm (2006).

In many GIS and GPS software packages the term **datum** or **geodetic datum** is used. It is a set of parameters that describe the relationship between a particular local ellipsoid and a global geodetic reference system (Seeber 1993). We can say that datum is a shorter name for local reference system with known relation to the global one.

2.3 Concepts of trajectory determination

Each navigation system must use some kind of sensor whose output can be used for computation of position, velocity and attitude. Note that not all applications require all three components of the state vector. There are several concepts and sensors for the determination of each component, but it is also possible to use only positioning sensors for determination of velocity (at least two position determinations separated by known time interval) and attitude (use two or more positioning sensors attached to the platform). Most of the navigation systems consist of several types of sensors. Navigation systems can be divided into three basis classes (Drane and Rizos 1998):

- **Signpost systems** determine their position by detecting proximity to a specific point.
- **Wave based systems** use electromagnetic or sound waves to measure direction, distance and/or its change to compute the position.
- **Dead reckoning (DR) systems** use sensors that measure the travelled distance (accelerometers or odometers) and sensors for determination of course of motion (compass, gyroscopes).

The navigation systems can be also divided into **self-positioning** and **remote positioning systems**. *Self-positioning systems* compute their trajectory using on-board computer, while *remote positioning systems* send their observations to a central processing station. The computed trajectory parameters are then sent back, if necessary. The GPS is an example of self-positioning system and radar is an example of a remote positioning system. It is obvious that any self-positioning system can function as remote positioning system if it transmits its trajectory to the central processing station. In this case we talk about indirect remote positioning system. Similarly, any remote positioning system can function as a self-positioning system, if the central processing station transmits the computed trajectory back to the platform. This is an indirect self-positioning system.

2.3.1 Signpost systems

Signpost systems can determine only position of the platform by identifying proximity to a known object (signpost), so the position of the platform is determined as the position of the

signpost. The simplest example is a person recognising an identifiable landmark. Automated versions are often called proximity beacon systems. Proximity can be detected by various sensors based on radio, light and sound waves or even by chemical sensors that can “sniff” presence of certain chemical substance. WiFi access points, GSM cell towers or stationary blue tooth devices can serve as signposts, since they transmit unique hardware address. Signpost systems can be self-positioning, if the platform’s sensors can identify the signpost and assign its position, or they can be remote positioning, if the platform is equipped with a unique tag that can be sensed and identified by the signpost. The advantage of signpost system is the simplicity. The existing non-specialised radio sources can be used as signposts. The disadvantage is non-continuous positioning (unless very dense signpost network exists) and relatively low accuracy, which is given by range of each signpost. For example, if a GSM cell tower covers area with radius 200 m, then the determined position can be up to 200 m wrong. On the other hand, it is possible to construct signposts with very short range, which guarantees high accuracy, for example a plate on the wall with coordinates encoded in bar code or RFID (Radio Frequency Identification) tag.

2.3.2 Wave based systems

Wave based systems use electromagnetic or acoustic waves to perform some kind of observation that relates the position of platform and reference point. Each reference point may have a transmitter or receiver, or both. The platform is equipped with a transmitter, receiver, reflector or some combination of these. The observation of electromagnetic and/or acoustic waves enables determination of the following observables: distance, direction, change of distance (or combination of these) between transmitter and receiver. The measured observables to or from one or more reference points are then used for calculation of position, velocity and attitude.

For example GPS satellites (reference points) are equipped with transmitters that broadcast 1.5 GHz electromagnetic waves. GPS receivers pick up the signal and based on the measured time of arrival determine the distance towards the satellites. The GPS receivers also measure the Doppler shift of the received frequency (change of the distance), which is used for velocity calculation.

The distance observable is derived from the measurement of time-of-flight, i.e. the time it takes for the signal to travel the distance between transmitter to receiver, or from the measurement of phase difference between signals. The distance measurement can be carried out by one-way or two-way method. In one-way method, the signal travels the distance just once: it propagates from the transmitter to receiver. Time of transmission is encoded to the signal and time of arrival is measured by the receiver clock. The time difference of these two events multiplied by velocity of light yields the distance. To obtain correct distance, the receiver and transmitter clocks must be synchronised or the

synchronisation (receiver clock error) must be computed using observation to at least one extra reference point. One-way method is utilised for example by GPS.

Wave based positioning systems are often named after the loci¹ that are used for calculation of position. For example the locus for distance measurement is sphere in 3-dimensional (3D) space or circle in 2D space, locus of directional measurement is line. Measurement of time difference of arrival (TDOA) of two signals that were synchronously sent by two distinct transmitters produces a hyperbolic locus - Figure 1c. Intersection of (at least two) loci is the navigated position. Figure 1 shows the concept of loci for three different systems.

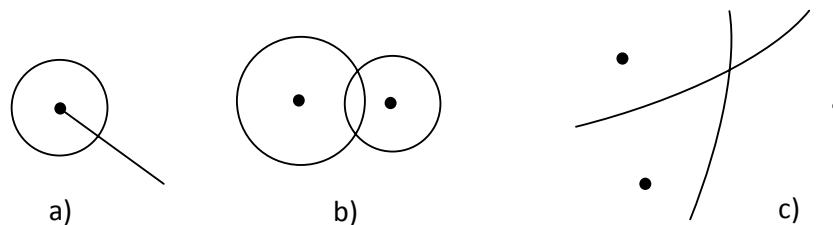


Figure 1. Loci of three different positioning systems. The dots show the reference sites. a) polar, or line-circular system, b) circular-circular and c) hyperbolic-hyperbolic.

2.3.3 Dead reckoning systems

Dead reckoning (DR) systems rely on sensors that can determine the change of position by sensing the direction and velocity (or acceleration) of the motion. The simplest example of DR system is odometer combined with compass. The odometer uses measured angular velocity of a wheel to compute the travelled distance and the compass gives the direction of the motion. Another common DR system is ***inertial navigation system (INS)***, which is a combination of accelerometers and gyroscopes. Inertial navigation system includes (beside sensors) also a computer with software that can process the output from sensors and to compute the state vector. A device equipped just with the accelerometers and gyroscopes, without ability to compute the state vector, is usually denoted as ***inertial measurement unit (IMU)***.

2.3.4 Comparison of navigation systems

Each of the above mentioned class of navigation systems has certain advantages and disadvantages. Generally, we cannot claim that one system is better than the other without taking into account the given application and its requirements. Table 1 summarises main advantages and disadvantages of three basic classes of navigation systems.

¹ locus (plural loci) is a figure formed by all possible positions that satisfy given observation

Table 1. Comparison of navigation systems

Systems	Advantages	Disadvantages
Signpost	<ul style="list-style-type: none"> Simple and robust Cheap sensors High accuracy possible 	<ul style="list-style-type: none"> Extensive infrastructure is required Intermittent update of position Only position determination (not velocity and attitude) Low or medium accuracy for radio beacons
Wave based	<ul style="list-style-type: none"> Accuracy does not vary in time Determination of full state vector is possible High rate of state vector update (up to ca 50 Hz) 	<ul style="list-style-type: none"> High infrastructure cost Vulnerable to interference and jamming Multipath problems Occlusion problems
Dead reckoning	<ul style="list-style-type: none"> Low cost for low accuracy Autonomous – no infrastructure is required Determination of full state vector is possible High rate of state vector update (> 100 Hz) 	<ul style="list-style-type: none"> High cost for medium and high accuracy Drift problem: accuracy gets worse in time, medium or high accuracy is kept only for several minutes To maintain accuracy, regular update by other sensors are necessary

Table 1 presents only main features that are common to whole class of navigation systems; there can be found more pros and cons for each particular system. But even from this general comparison, it is evident that none of the systems have only advantages and the most obvious way to eliminate the disadvantages is to combine different types of navigation systems and sensors. For example standard GPS, which belongs to wave based systems, provide homogenous medium accuracy with relatively low update rate (1 s), while an inertial navigation system can provide high update rate (>100 Hz) with high short term accuracy. Figure 2 illustrates difference between homogenous accuracy and drift.

Combination of these two systems can provide high update rate and the homogenous accuracy at the same time.

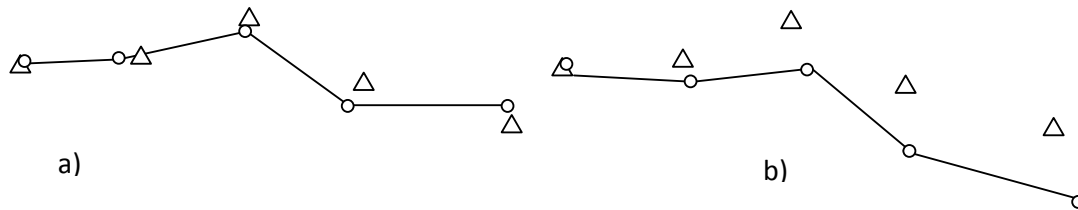


Figure 2. Homogenous accuracy a), drift b). Triangle denotes true and circle determined position.

3 Overview of navigation systems

3.1 Global navigation satellite systems (GNSS)

Class: wave based self-positioning systems

So far, the only fully operational GNSS is the NAVSTAR GPS (Navigation System with Timing and Ranging Global Positioning System) developed and operated by Joint Program Office (JPO - <http://gps.losangeles.af.mil>) and directed by U.S. Department of Defence. Russian counterpart GLONASS (GLObal Navigation Satellite System) is also operational, but at this time (August 2009), there are only 20 active satellites. According to the system specification, full GLONASS constellation consists of 24 satellites. Current status, official documents and other information about GLONASS is available at the official GLONASS web page <http://www.glonass-ianc.rsa.ru/>. Currently there are two systems under construction: Chinese Compass and Galileo being built by European Union.

All the above-mentioned GNSS are based on the same principle: receiver measures time it takes for the signal to travel from satellite to the receiver. The satellites are continuously monitored by control segment, which is a network of control stations. Based on this monitoring, the control segment computes satellite clock corrections, orbital and other parameters. All this information is then uploaded to satellites and made available to users through the satellite signal.

Individual GNSS differs from each other by implementation details, like signal frequencies, the way of signal coding, working reference frames etc. Below we describe the main properties of GPS, but most of the statements apply to other above-mentioned GNSS.

GPS is spherical-spherical system, which means that the position of receiver is determined by measuring distances towards available satellites. The distances are derived from signal's travel time measurement and they are called pseudo ranges, since they include receiver's clock error. This error is estimated together with position. GPS satellites transmit signal on two carrier frequencies: L1 = 1575.42 MHz and L2 = 1227.6 MHz. The GPS signal is attenuated by obstructions like trees or buildings, which makes it more difficult or impossible to navigate in urban corridors or inside the buildings.

Accuracy: medium, high when augmented

The accuracy of position determined by GNSS depends on several factors. The most crucial factors affecting navigation accuracy are: the number of satellites seen by the receiver, their distribution on the sky, signal strength, signal reflections (multipath) and atmospheric delay (by ionosphere and troposphere). According to Department of Defense (2001) the Global Average Positioning Domain Accuracy is better than 13 m on 95 % level of probability for horizontal position and 22 m for vertical position. Corresponding specification for Worst Site Positioning Domain Accuracy is 36 m and 77 m.

The accuracy can be improved by augmentation to decimetre or even millimetre level. The basic principle of GPS augmentation is to difference out common errors affecting observations at two (or more) receivers. One of the receivers (reference receiver) is set up over a point with precisely known coordinates. This receiver computes and transmits so called differential corrections, which are then applied to roving receivers. The corrections can be transmitted in different ways: by radio or GSM modems, through internet or via geostationary satellites.

Availability: $\geq 99\%$ (Department of Defense 2001)

In support of the service availability standard, 24 operational satellites must be available on orbit with 95% probability (averaged over any day). At least 21 satellites in the 24 nominal plane/slot positions must be set healthy and transmitting navigation signal with 98% probability (yearly averaged). In reality, there have been always more than 24 active GPS satellites since the system was declared operational in April 1995, which means that the availability has been always 100%.

Capacity: unlimited number of users

There is no limitation on the number of simultaneous users, since there is only one-way communication between receiver and satellite, so the system is not “aware” of number of users.

Coverage: global

Full constellation of GPS satellites guarantees global coverage. Probability, that a user can see at least 4 satellites with elevation greater than 5° over horizon during any 24 hour interval, averaged over the globe, with PDOP² < 6 is larger than 99.9% (Department of Defense 1995). This statement is valid for nominal 24 satellites constellation. In reality, there have been always more than 24 active satellites (at time of writing 32) therefore we can claim that the coverage is 100% of the globe.

Dimensions: 4

If GPS receiver receives signal from at least four satellites, 3-dimensional position and receiver clock correction can be computed. The accuracy of receiver clock error determination is better than 40 ns (Department of Defense 2001). Some receivers enable also 2D positioning, if there are only 3 satellites available. In this case the height is not estimated, but it is considered as known, with last known value.

Integrity: low

GPS satellites have advanced self-controlling facility, i.e. “they remove themselves from service when they experience any of specified failure modes. When a service failure occurs that is not covered by the automatic removal capability, the U.S. government will remove the satellite from the service in a prompt manner, subject to current monitor station and ground antenna visibility and reliability constraints” (Department of Defense 2001). The current control segment provides approximately 93% global coverage, which means that in worst case scenario, it may last up to 6 hours until a satellite failure that is not detected internally is reported by the control segment (Hofmann-Wellenhof et. al. 2003).

There are several possibilities of improving the integrity GPS. One option is to use additional set of monitor stations. This integrity monitoring function is built in most of the augmentation systems that provide differential corrections. Another option is the integration of GPS with another, independent navigation system. The third possibility is to use receiver autonomous integrity monitoring algorithms. Such algorithm can detect a

² PDOP = Positional Dilution of Precision is a unitless number describing the effect of distribution of observed satellites on accuracy. Lower PDOP gives higher accuracy.

failure (erroneous observation) only if 5 or more satellites are observed. An overview of various receiver autonomous integrity monitoring algorithms is given in Brown (1996)

Reliability: $\geq 99.94\%$ global average (Department of Defense 2001)

This standard is based on 3 service failures per year, lasting no more than 6 hours each, measurement interval of one year; average of daily values within the service.

Update rate: 1 Hz

1 Hz is a default update rate for all GPS receivers. However, there are advanced GPS receivers available on the market, which can update position at higher rate, up to 50 Hz.

Infrastructure

To build a GNSS is a costly enterprise; according to Galileo information video that was available at Galileo official web page in 2004, the cost of whole system was estimated to €3.2 billion. GPS infrastructure involves space segment (GPS satellites) and ground control segment (monitoring stations). Some other GNSS may include also terrestrial and/or satellite radio communication links. This is the plan for GALILEO. The communication links will enable dissemination of differential corrections as well as integrity messages. GPS augmentation services and the associated communication links are operated by organisations independent on U.S. Department of Defence and therefore are not considered as a part of NAVSTAR GPS. However, we consider them as a part of GPS infrastructure.

As we mentioned earlier, the main weakness of GPS (and also other GNSS) is very weak signal power, which makes it difficult or even impossible to use GPS for city navigation. It should be mentioned that during last decade there has been extensive research in development of more sensitive GPS receivers, which are able to process very weak signal and thus navigate in indoor environment. As an example, we can mention high sensitive chips developed by company SIRF (<http://www.sirf.com/>) or BROADCOM (<http://www.broadcom.com/>). G. MacGougan et al. (2002) performed tests with ordinary and high sensitive GPS receivers in different environments. The results of the tests show clearly better performance in obstructed areas. For example, high sensitive receiver provided position fixes in 93 % of driving time through streets of Vancouver city. The corresponding percentage for common GPS receiver was around 15%. If the receivers were placed in a concrete garage, only the high sensitive receiver was able to track the satellite signals and to deliver position. Another modification that improves performance of high sensitivity receivers is to use so called Assisted GPS (A-GPS), where the signal processing is supported by externally provided information (LaMance 2002). For example an A-GPS receiver can download ephemeris and other information via GSM, which significantly saves processing time and power consumption of the receiver. Tests performed by Binghao et al.

(2009) show that A-GPS receiver provide the position faster (shorter time of the first fix after turning on receiver) and it can process weaker signal (compared to non assisted GPS). Both test also showed that the accuracy gets worse when GPS signal is weak, so we can say that indoor accuracy of GPS position is low.

Today the only solution to preserve “normal” accuracy of GPS in indoor applications is to use “pseudo satellites”, in literature often denoted as pseudolites. Pseudolite is a device, which sends GPS-like signal. The concept of the pseudolite was proposed in the 1970’s, even before the launch of the GPS satellites. In fact, pseudolites were originally designed to test the initial GPS user equipment (Harrington & Dolloff, 1976). The use of pseudolites in positioning and navigation was first discussed by Beser & Parkinson (1982) and Klein & Parkinson (1984). They are used as “additional” artificial satellites installed for example near airports (Van Dierendonck 1999), city canyons or indoors. Although the pseudolites transmits signal similar to GPS, the receiver must be modified to be able to receive and use pseudolite signal. The reason is a difficulty, called near-far effect, due to the large difference in distance of satellites and pseudolites to the user. Continuously broadcasting pseudolite would cause interference with the satellite signal, because it is much stronger due to short distance. This problem can be circumvented by pulsing the pseudolite signal in a regular pattern. Strong pseudolite signal penetrates the walls and obstacles much more than weak satellite signal. This enables navigation even inside the buildings, without necessity of free view towards the transmitters. The pseudolite systems can operate in combination with GPS satellites, or completely independently from GPS. They are capable of high accuracy, even on centimetre level. Main drawback of such systems is high cost of the infrastructure and the necessity of modification of GPS receiver. This modification is on firmware level, so it is possible to use the existing receivers with their software.

The cost of one pseudolite ranges from 10 000 to 100 000 USD (Rizos 2005). So far, the pseudolite technology has been used mostly for academic and research purposes, but there are some commercial systems available on the market. For example company Center for Remote Sensing, Inc (<http://www.cfrsi.com/>) offers software based pseudolite system consisting of both pseudolite transmitters and receivers. Another company, which developed pseudolite system, is Locata Corporation Pty Ltd, (<http://www.locatacorp.com/>). However, this company does not sell the system directly; they cooperate with larger companies, like Trimble or Leica.

3.2 Terrestrial radio navigation systems for aviation and maritime use

These systems are primarily designed for aviation and maritime use, and therefore their use for city navigation is quite limited and therefore we give just brief description here. The main goal of these systems is the determination of horizontal position. Transmitters with known position define the reference frame. Based on the signals from the transmitters, the receiver computes its position. The observables obtained from the signal can be directions, angles, distances, pseudoranges or their combinations. The systems can be divided into two groups: point source and area based systems.

3.2.1 Point source systems

Direction finders

The basic idea is the determination of the direction to a known transmitting station. The locus is a straight line. Applying this idea to two different and known transmitting stations, the position can be determined as the intersection point of the two loci. In its simplest form, direction-finding equipment consists of a conventional radio receiver with an antenna in the form of a coil of wire, which shows strong directional properties - Figure 3. The radio signal of the transmitter induces currents in the arms AB and CD whose strengths depend on the orientation of the loop. The currents are equal in amplitude and phase if the plane of the loop is exactly orthogonal to the direction of the arriving signal (null position of the loop). The receiver then reads no signal, because the currents eliminate each other.

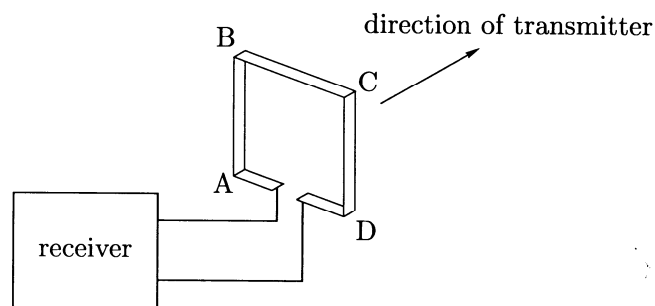


Figure 3. Direction-finding loop (Hofmann-Wellenhof 2003)

In practice, first a known transmitter is tuned in. Then the loop is rotated until no signal is received, which means that the direction orthogonal to the plane of the loop points toward the transmitting station. This direction provides one loci. An automatic direction finder (ADF) unit is equipped with a motor that rotates the loop antenna to keep it always in the null position. The motor also activates a needle (similar to a compass needle) that indicates the position of the loop and, therefore, the direction of the transmitter, which is tuned in. Such ADF units can operate on any broadcast station, communication station, navigation

station, or any other kind of radiating system broadcasting a continuous carrier on a frequency that the radio can receive. Virtually all aircraft and ships are equipped with direction finders. Direction-finding unit can also be used to locate the source of the radio signal; for instance finding lost aircraft. A refinement of the loop antenna is the goniometer direction finder, where two fixed loops are placed at right angles. By measuring the currents from both loops, the direction of the incoming radio signal can be computed.

Direction finders are simple devices, which can use existing known radio sources as infrastructure. There are also specialised beacons called non-directional beacon (NDB). NDB is an omni-directional transmitter broadcasting continuously a radio signal. A three-letter Morse code allows for discrimination between different sites.

The main problems of the direction finding systems are disturbances: especially the night and mountain effects. At night the beacons are vulnerable to interference from distant stations, because radio signals are reflected from the ionosphere. In mountainous, urban or indoor areas, NDB signals may be reflected by the terrain causing fluctuations of the indicated direction.

More advanced direction finding system is **VHF omnidirectional range (VOR)**. VOR is a navigational aid that operates in the VHF (very high frequency) part of the frequency spectrum (108-118 MHz). VORs are radio beacons transmitting a signal, which provides directional information. They are used for aircraft navigation. The basic principle can be explained using an analogy with light signals: imagine a rotating beam at a lighthouse, which becomes visible for the pilot if its direction coincides with his looking direction. When this rotating beam moves through a reference direction, e.g. north, the beacon flashes a second light omni-directionally; thus, vessels or aircrafts in arbitrary directions might see this light. The time elapsed between these two events is a measure for the angle between the vessel or aircraft and the reference direction. In reality, the light signals are replaced by radio waves. A VOR ground station electronically rotates a directional antenna at 30 rounds per second. The antenna transmits two signals: the first one is frequency-modulated sine wave with frequency of 30 Hz, called reference signal and the second one, called variable signal, which is 30 Hz amplitude-modulated wave. The reference signal is omni-directional, i.e. its phase is the same in all directions, while the phase of the variable varies from 0° to 360° around the station. The phase difference between the two 30 Hz signals varies directly with the bearing of the aircraft. The VHF carrier is also modulated by a 1020 Hz Morse code identification signal and by a voice signal (300-3000 Hz). Depending on the height of an aircraft, VORs have a range of about 400 km; however, they are restricted to line-of-sight propagation, which is why they are unsuitable for city navigation.

Distance measuring equipment (DME)

The distance measuring equipment (DME) measures the slant range between the ground station and the aircraft. DME measures the propagation time of the signal transmitted by the aircraft, received by the ground station and retransmitted back to the aircraft. The DME operates in the UHF³ band and is, therefore, restricted to line-of-sight transmission. With adequate height, the pilot can receive en route DME signals at distances over 400 km. Each ground station is designed to handle about 50 aircrafts simultaneously. The capacity limitation arises from the two-way communication. When the ground station is collocated with a VOR station, the resulting VOR/DME combination forms the basis for the standard ICAO (International Civil Aviation Organization, www.icao.int) short-range navigation system, which enables to compute position of the aircraft using only single VOR/DME station. Achievable 2σ -accuracies (95% probability) for VOR/DME are 1.4° for VOR and 185 m (or 0.1 nautical miles) for DME.

3.2.2 Area-based systems

In contrast to the point source systems where, primarily, one transmitting source and the appropriate receiver were considered, area-based systems rely on more than one transmitter. The transmitters cover the area of interest. The principle of area-based systems can be explained with help of Figure 4. Consider two continuous wave signals synchronized in phase at the master and the secondary transmitting station. At points A and C (and at each intersection of the waves) the receiver will receive the two signals in phase. Moving from A to C, the receiver crosses one "lane".

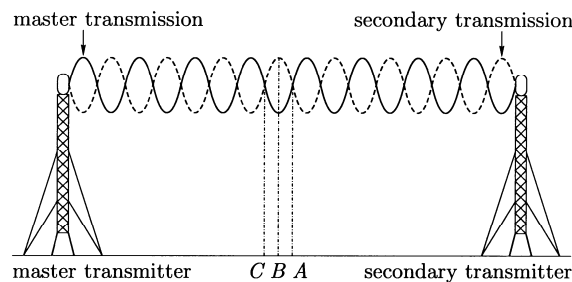


Figure 4. Principle of area-based systems. (Hofmann-Wellenhof 2003)

The width of the lane corresponds to one half-wavelength of the transmitted frequency. B indicates a location of maximal phase difference. The phase difference depends on the difference in distances to the master and secondary transmitter. The geometrical place of all points having constant difference in distance from two fixed points is hyperbola.

³ UHF – ultra high frequency, range 300 – 3000 MHz

Therefore it is possible to plot loci for all possible receiver positions where the received signals from master and secondary station are in phase as a set of hyperbolas – Figure 10.

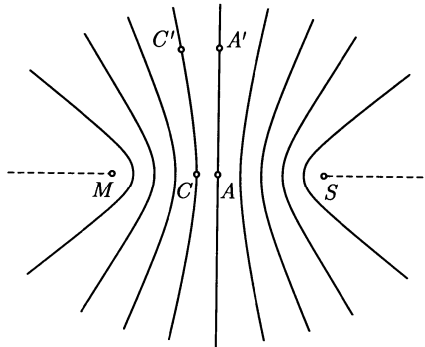


Figure 5. Loci for master and secondary station. (Hofmann-Wellenhof 2003)

A receiver may not distinguish between positions A and A' or C and C'. On the other hand, the change of the number of traversed lanes is known because they are registered by the receiver. The intersection of two hyperbolic loci defines the receiver position in two dimensions. Hyperbolic systems are incapable of providing accurate estimates of the height because of the geometry of land-based transmitters relative to any user close to the surface of the earth.

Currently there are two systems based on this principle: LORAN-C and Chayka. LORAN system was developed at the Radiation Laboratory of the Massachusetts Institute of Technology (MIT) at the times of World War II. In 1958, the first Loran-C system became operable. The Russian Chayka system is very similar to Loran-C. Before the satellite navigation systems were available, these systems were the most important for marine and aviation navigation. The signal covers most of the coastal areas on northern hemisphere; for detailed map with coverage search LORAN on Wikipedia. Today, the area-based systems are used as backup systems in case of GNSS navigation failure. Absolute accuracy is in size of 460 m (Hofmann-Wellenhof 2003), which is insufficient for city navigation.

3.3 Cellular communication networks

Class: signpost or wave based, self or remote positioning systems

Cellular communication networks allow the determination of the two-dimensional position of every user of a cellular phone or modem - denoted as mobile station (MS). This is a crucial functionality of the communication network itself, since the system roughly needs to know where its users are located for establishing communication links. There are number of advantages of cellular telephone positioning systems:

- Already built infrastructure with allocated frequency spectrum
- Infrastructure (number of base stations) is denser in more populated areas (cities)
- Many users
- The cellular system provides a two-way communication link

The principal disadvantage of this technology is that the cellular systems have not been designed for positioning, i.e. most of the areas are covered just by base station. There are several ways of position determination using cellular networks.

The most straightforward method is **cell-oriented positioning**, where the base station (BS) is considered as a signpost - Figure 6 left. This method allows for self-positioning of the cell phones. The accuracy of such positioning depends on cell size, which strongly depends on the population density of a given region. As a rule of thumb, the higher the population the higher is the number of transceivers in the respective region of the cellular network and hence smaller cell size and higher accuracy. Approximating the cell area by a circle, the radius of a cell may vary between 100 m and 1-5 km in urban areas (pico and micro cells) and up to 20 km in rural environments (macro cells).

The accuracy may be improved by applying **angle-of-arrival** technique, where the base station is equipped with array of antennas directed in different directions around the base station. Thus; the area of a specific sector inside the cell defines the position of the MS (Figure 6, right). In this case only remote positioning is possible, since the mobile phone does not receive information about the particular antenna it communicates with. If at least two base stations at different locations are able to determine the angle of arrival of the signal, the position of mobile station can be computed. Generally, the accuracy of the angle measurement decreases with increasing distance between the MS and BS mainly due to scattering environment. The angle-of-arrival method is more suitable for macro cells. This is due to the fact that base stations in macro cells are usually elevated well above the local terrain, reducing the problem of scattering objects in close vicinity of the base station. In

case of micro cells, non-line-of-sight situations may lead to gross errors due to scattering objects close to the base station.

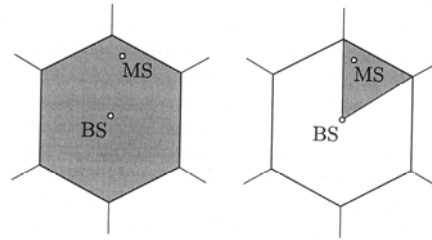


Figure 6. Cell-oriented positioning (left), supported by an antenna array (right) (Hofmann-Wellenhof 2003).

The distance from base station can be determined by **signal strength technique**. Positioning using signal strength measurements employs a mathematical model describing the loss of signal strength as a function of the distance between transmitter and receiver. In an ideal environment, the geometrical locus of a signal strength measurement is a circle where the radius depends on the measured signal strength. Thus, positioning is based on a multiple ranging technique. A number of error sources influence the accuracy of the position estimate. The primary source of error is multipath and shadowing by fixed and/or moving obstacles. These effects strongly distort the circular shape of lines of equal signal strength.

A better measure of distance between mobile and base station is measured travel time of signal. Two different approaches are used for **time-based methods**: time of arrival (TOA) and time difference (TD) measurements. In case of cellular positioning, the abbreviation TDOA for time difference of arrival is more frequently used. Time determination may be based on (ambiguous) phase measurements, pulse transmission, or code techniques. In a TOA system, the position of a mobile station is determined by measuring the propagation time of a signal travelling from the mobile station to several base stations (remote positioning) or vice versa (self-positioning). Usually, the clock of the mobile device is not synchronized with the network stations. Thus, pseudorange positioning is required. A TOA system has two major disadvantages. Firstly, it requires a precisely synchronized base station network. Secondly, the transmitted signal has to be time-tagged to enable pseudorange measurements. In addition, non-line-of-sight propagation caused by signal reflections has a significant influence on the accuracy. In a time-difference-of-arrival (TDOA) system, the position of the mobile station is determined by means of time differences rather than by absolute time of arrival measurements. Thus, the position determination is done in hyperbolic mode, similar to LORAN-C. The TDOA method requires that the base station network is synchronized but does not impose any requirements on the transmitted signal. A special implementation of a TDOA system is the **enhanced observed time**

difference (EOTD) method, which supports TDOA-based self-positioning. In this case, location measurement units placed at known positions receive the same signals from the surrounding base stations as the mobile stations. This allows determining the clock offset between each pair of base stations. Typically, one location measurement units is needed per three to five base stations. This concept is similar to differential GPS.

Another method of positioning in cellular networks is the use of wide **signal-strength signatures**. In addition to the 6-strongest cells traditionally used in the GSM standard, the wide signature, or fingerprint includes readings from additional cells that are strong enough to be detected, but too weak to be used for efficient communication. A signal strength signature is defined by the signal strength characteristics at the user site. The signature is analysed and compared with the entries of a database by means of pattern recognition techniques. The database is continuously extended by new position measurements via suitable learning algorithms. Disadvantage of this method is that any change in the environment will change the signature, so the signature database must be updated continuously.

Accuracy: medium – low

Cell oriented positioning: 100 m – 20 km, Zandbergen (2009) reports 599 m median error.

Time based methods: 270 – 380 m for GSM networks, 20 – 27 m for UMTS networks (Hofmann-Wellenhof 2003)

Signal-strength signatures: achievable 7 – 18 m (Otsason et al. 2005)

Otsason et al. (2005) describe experiments, where they mapped fingerprints (signal strength) of all detectable GSM signals in three multi floor buildings. They report 7 – 18 m accuracy at 90% probability level. It should be pointed out that they performed extensive signal mapping – around 200 point in each building to be able to achieve this accuracy. Moreover, they did not study the effect of weather conditions on signal strength stability. Similar experiment described in Lakmali and Dias (2008) shows accuracy 17.3 m (95%) in indoor, 276 m in urban and 700 m in rural environment, respectively.

Availability: depends on availability of cellular networks. No number found in the reference literature; estimation based on personal experience: close to 100 %

Capacity: unlimited for self positioning methods, where only one-way communication is required, i.e. mobile station reads the signal from base stations. For remote positioning, there is limitation for number of simultaneous users given by the capacity of the base station, which is around 10 000 mobile stations (from specification of UltraWAVE base station produced by company ADC www.adc.com).

Continuity: no information available, estimation: close to 100%

Coverage: local

The cellular networks do not cover whole globe. Usually only populated areas are covered by GSM signal. For Western Europe, the coverage is almost 100%, only small mountainous areas are not covered. The updated coverage maps are available at <http://www.gsmworld.com/>.

Dimension: 2

The geometry of base station does not allow for reliable height determination. The height can be adopted from the height of closest base stations.

Integrity: unknown

The cellular networks are not designed for positioning. According to author's knowledge there is no independent monitoring of integrity with respect to positioning.

Reliability: no information available**Update rate:** 2 s (Ramm et al. 2005)

Update rate is limited by the performance of mobile station in case of self-positioning and by performance of base station in case of remote positioning methods.

3.4 The Active Badge Location System

Class: signpost remote positioning system

The Active Badge Location System (ABLS) was one of the first indoor location tracking systems developed specifically for indoor office environments and was first developed at the Xerox Palo Alto Research Center. Afterwards the system was improved at Olivetti Research Ltd. and later in AT&T Cambridge Laboratory. The system is described in Want et al. (1992). Active badges are essentially low-cost, low-power infrared beacons emitted by the badge worn by a user (Cook and Sajal 2005). The beacons are transmitted intermittently, with a period from 10 s to 6 min. Each individual badge transmits unique code. Duration of a single transmission is 0.1 s. The receiving sensors, which are deployed at various locations, detect the presence of individual badges. The location of a particular active badge (user) is associated with the reading sensor that currently reports a reading from the badge.

Infrastructure

The active badge infrastructure consists of a group of Badge sensors (readers) installed in various locations of the building. The sensors are connected together by a 4-wire cable. Two wires are for power supply and two for data communication with the network controller, which is an ordinary PC workstation; see Figure 7. Data received by sensors are sent to the main server, which displays the position of all tags (worn by users).

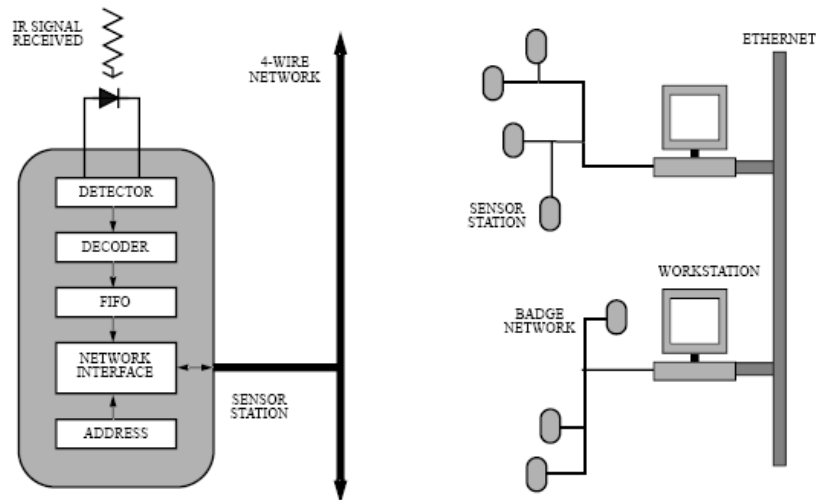


Figure 7. Badge sensor and telemetry network (Want et al. 1992).

Accuracy: high, medium

The accuracy is essentially governed by the communication range of the active badge, which is usually size of a normal room (6 - 10 m). In the case where there is only one reading sensor in a large conference room the accuracy is in medium range (10 – 50 m).

Availability: not specified, estimated close to 100 %

The available articles do not provide any numerical value of availability. We can deduce that the availability can be restricted due to power failure or sensor failure.

Capacity: not specified, estimated: thousands of users

The available articles do not provide any numerical value on capacity. Theoretically, the only limitation of number of users is given by number of available addresses that can be assigned to the individual active badges. Another issue that should be considered is the number of active badges that can be detected by one reading sensor. Because the signals have duration of only one-tenth of a second, there is approximately a 2/150 chance that

two signals will collide when two badges are placed in the same location. For a small number of people, there is a good probability they will all be detected. Even so, in order to improve this chance, the beacon oscillator has been deliberately designed around low-tolerance components. The components used for the beacon oscillator have a 10% tolerance rating; for two badges to remain in synchronization for even a single 15-second beacon period, the components would have to be matched better than 1.4%. It is very likely that two badges, which at some instant may be synchronized, will have slightly differing frequencies and thus lose synchronization within a few beacon periods. In practice, synchronization has not been a problem (Want 1992).

Coverage: local, non-continuous

The coverage is given by number and distribution of the reading sensors. The system is designed for office environments, so we can say that coverage is limited to one or several buildings. There may be places within the building that are not within the reach of any reading sensor, like toilets or obstructed places within rooms. For example, the reading sensor may not detect the active badge worn at belt or waist position, if the wearer is seated at a desk.

Dimension: 2 or 3

The position of user is associated with the position of the reading sensor, which must be determined by another method. The dimension of the Active badge system depends on the method of determination of position of the reading sensors.

Integrity: not specified, estimated high

Although the integrity issue is not treated in the reference literature, we can assume that the level of integrity is high; since the main server can communicate with all reading sensors it is possible to detect their failure.

Reliability: no information available. The same note as for availability applies here.

Update rate: 1/10 – 1/600 Hz

The update rate depends on particular implementation. Since the active badges are powered by a small battery, higher rate would shorten its lifetime. As reported by Want et al. (1992), the batteries last for about one year at update rate 1/15 Hz.

3.5 Active bat

Class: wave based, remote positioning system

The Active Bat system (Harter et al. 1999) is an indoor navigation system that employs ultrasonic (sound waves) technology. Persons wear a small device, called active bat - Figure 8, which emits short ultrasonic pulses, which are then captured by at least three sensors mounted at reference locations on walls or ceilings. Receivers are connected by a wired network - Figure 9.



Figure 8. A Bat unit (Harter et al. 1999)

A base station periodically transmits a radio message containing a single identifier, causing the corresponding Bat to emit a short unencoded pulse of ultrasound. Simultaneously, the ultrasound receivers in the rooms covered by the base station are reset via the wired network. Receivers monitor the incoming ultrasound and record the time of arrival of any signal from the Bat. Using the speed of sound in air (which can be estimated from the ambient temperature), the times-of-flight of the ultrasound pulse from the Bat to receivers can be converted into corresponding Bat-receiver distances. After a distance-measuring pulse has been emitted, the base station waits for reverberations of the pulse to die out before triggering another Bat, ensuring that receivers can ascribe incoming ultrasonic signals to the correct Bat. This process divides time into timeslots, each of which can be used to locate a single Bat. In typical office spaces, reverberations may take up to 20ms to die away, implying that there may be up to 50 timeslots (and hence location updates) per second per base station. (Harter et al. 1999).

The Active Bat system enables also determination of orientation of person or object to which the Bat is attached. This is done by either attaching more sensors to the same person, or by deducing orientation by identifying the sensors that received ultrasonic pulse. The accuracy of orientation is low – some tens of degrees.

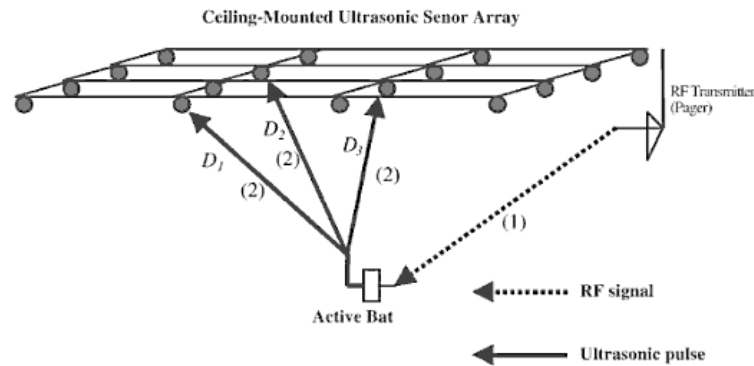


Figure 9. Active bat trilateration. (Cook and Sajal 2005)

Infrastructure

The infrastructure of the Active Bat system includes ultrasonic sensor array, a radio frequency transmitter and a server with dedicated software. Number of sensors in array depends on the area size to be covered.

Accuracy: high, cm – dm level

Capacity: 65535 Bats using 16 bit address space

Availability: not specified

Coverage: local, non-continuous

The coverage is given by number and distribution of the ultrasound receivers. The system is designed for office environments, so we can say that coverage is limited to one or several buildings. There may be places within the building that are not within the reach of any ultrasound receiver, like toilets or obstructed places within rooms.

Integrity: not specified

Reliability: no information available

Update rate: up to 50 Hz, if only single Bat unit is tracked

The limited number of timeslots must be efficiently distributed between the set of Bats to be tracked. Each timeslot can be allocated to any Bat by the base station. Individual Bats can be tracked at different rate, which can be dynamically changed.

3.6 Cricket

Class: wave based, self-positioning system

Cricket Location Support System developed at MIT (Priyantha 2000) uses a combination of RF and ultrasound technologies to track the location of mobile objects in an indoor environment. Cricket uses beacons to disseminate information about a geographic space to listeners. A beacon is a small device attached to some location within the geographic space it advertises. Typically, it is obtained by the “owner” of the location (e.g., the occupant of a room in an office or home, or a building administrator) and placed at an unobtrusive location like a ceiling or wall. Cricket beacons are inexpensive (\$10) and more than one of them can be used in any space for fault-tolerance and better coverage. A listener attached to person, or object is a small device that listens to messages from beacons, and uses these messages to infer the space it is currently in. When a mobile computer has a listener attached to it, the listener constantly listens to beacons to infer its location. As the computer (e.g., a hand-held computer carried by a person) moves in a building, the navigation software running on it uses the listener API to update its current location. Then, by sending this information securely to a map server (for example), it can obtain updates to the map displayed to the user.

Cricket beacon is a combination of radio and ultrasonic transmitter. On each transmission, a beacon concurrently sends information about its position over RF, together with an ultrasonic pulse. When the listener hears the RF signal, it uses the first few bits as training information and then turns on its ultrasonic receiver. It then listens for the ultrasonic pulse, which will usually arrive a short time later. The listener uses the time difference between the receipt of the first bit of RF information and the ultrasonic signal to determine the distance to the beacon. The value of the estimated distance is used to decide which the closest beacon is. To avoid collisions between signals sent by two or more beacons simultaneously, the beacons transmit signal in random intervals, approximately 4 times per second. This ensures that the beacons will not transmit the signal synchronously.

Infrastructure: combined RF and ultrasonic beacons

Accuracy: high - medium

The accuracy depends on the density of the beacons. Usually, there is one beacon in each room, so the accuracy can be in range 5 – 10 m.

Capacity: unlimited number of users

Availability: not specified

Coverage: local, non-continuous

The coverage is given by number and distribution of the beacons. The system is designed for office environments, so we can say that coverage is limited to one or several buildings. There may be places within the building that are not within the reach of any beacon.

Integrity: not specified

Reliability: no information available

Update rate: 4 Hz

3.7 RFID Location Systems

Class: signpost or wave based, remote or self positioning system

RFID - Radio-frequency identification is the use of an object (typically referred to as an RFID tag) applied to or incorporated into a product, animal, or person for the purpose of identification and tracking using radio waves. Some tags can be read from several meters away and beyond the line of sight of the reader. (www.wikipedia.com). There are two main classes of RFID systems, **passive tags** and **active tags**. *Passive tags* are the most widely used. They depend on the wireless signal from the reader to provide the power to activate the chip and to allow its data to be read. Passive tags are available in three main types; Low Frequency, High Frequency and Ultra High Frequency. They are substantially lower in cost than active tags and have an indefinite life but can be read over shorter distances. *Active tags* have their own on-board battery power and do not (or only partly) depend on the power provided by the reader. They are more expensive than passive tags and the battery has a finite life (typically up to 5 years) but they do offer significantly greater read distances. The read distance depends on many factors: the type of tag technology (LF, HF, UHF), the design and quality of the tag itself, the antenna used on the reader, the environment of the reader and tag (intervening materials, what the tag is mounted on, electrical interference). However, in general terms the following read distances can be achieved:

LF: 3cm - 12cm

HF: 5cm - 6cm

UHF: up to 8 - 10 metres

Active Tags: up to 100 metres

Tags have a quite limited storage capacity and normally only hold an identification number that allows them to be linked to a record in a database. Different tag technologies have different storage capabilities:

LF: 64bits - 2k bits

HF: 0.5k - 4k bits (specials to 16k)

UHF: up to 240 kbit

Active Tags: Typically up to 1012kbit

As an example of RFID based system is 3D-iD location system commercially released in 1999 by company RF technologies. The system employed active RFID tags and proprietary base stations. Today the improved system is sold under name **PinPoint Real Time Location System (RTLS)**. In the RTLS base station antennas placed at well-known reference points emit radio frequency signals at 2.4GHz. The base stations are synchronised. Tags located on the mobile devices respond to these signals, with an identification code uniquely identifying the mobile device. These response signals are measured by multiple receiving antennas (similar to the Active Bat technology) and are then triangulated at a centralized server to resolve the location of the mobile device. The triangulation technology achieves 1 - 3 m accuracy. This system suffers from the disadvantage that each receiving antenna has a narrow cone of influence, which makes ubiquitous deployment quite expensive. Thus, it is best suitable for large indoor spaces like hospitals or warehouses. Moreover, the Pinpoint system is essentially paging-based, with the network polling the mobile devices according to some schedule and the targeted mobile device reflecting back a response to each such poll.

Example of another location tracking system that employs Active RFID tags is the **LANDMARC** (Location Identification Based on Dynamic Active RFID Calibration) system (Ni et al 2004). It deploys a group of Active RFID readers over the smart environment with partial overlap between the coverage areas of different readers, governed by the power levels associated with each reader. By properly placing the readers in appropriate reference locations, the entire smart environment can be conceptually divided into multiple zones, each consisting of a unique collection of RFID readers that are within communication region of that entire zone. For example, given five readers, R1, R2, R3, R4 and R5, we may set the power levels to define two zones: Z1 comprising (R1, R3, R5) and Z2 comprising (R2, R3, R4, R5). To determine the location of a particular RFID tag, the system can then merely look up the identity of the readers that receive a location update from the RFID tag. The location of the tag can then be localized to the zone corresponding to the set of active readers that detect the beacon from the tag. However, this naive approach is not very useful, since the propagation characteristics of the indoor environment change very rapidly, making it impossible to associate a set of RFID tags with a physical zone in any meaningful way. To overcome this problem, the LANDMARC system uses a set of RFID reference tags (called landmarks). The LANDMARC readers receive updates not only from the tag being tracked, but also from this set of static reference tags, whose location is well known and hence the signal strength can be correlated with the distance to the readers. Based on this correlation,

the distance between a particular RFID tag and readers can be determined and position of the tag computed (Cook and Sajal 2005). The readers do not need to be synchronised.

In the study performed at National Institute of Standards and Technology (Miller 2006), the RFID tags were used in indoor self-positioning system: the tags were placed at reference locations and the reader was placed at the mobile unit. The tags serve as signposts; the reader obtains coordinates of the tags. In this study, the position readings were used as updated for dead reckoning system.

Infrastructure of RFID based systems includes RFID tags and/or readers, communication network and server in case of remote positioning systems.

Accuracy: high

Accuracy for methods, where the distance is determined by measuring time-of-flight is on metre level (1 - 3 m for PinPoint system, Cook and Sajal 2005). The same accuracy was reported by Ni et al (2004), where the distances were derived from signal strength information. The tags cost from several cents (passive) to several dollars (active). The readers usually cost from several hundred US dollars to 2 000 \$ (www.rfidjournal.com).

Capacity: unlimited for self-positioning systems, limited for remote positioning systems. The limitation is in the number of users that can be tracked simultaneously, which is constrained by the update rate of the readers, by capacity of communication links and processing power of server.

Availability: not specified

Coverage: local, non-continuous for signpost systems, continuous for wave based systems

The coverage is given by number and distribution of the readers (remote systems) or RFID tags (self positioning systems).

Integrity: not specified

Reliability: less than 100%

No RFID tag can be detected with 100 % probability. The detection success depends on the distance and orientation between reader and tag and on materials that surround the environment, which can block, absorb or reflect the radio waves.

Update rate: up to 1600 Hz (Brown 2007)

3.8 WLAN and Bluetooth based location systems

Class: signpost or wave based, remote or self positioning system

The basic idea of WLAN⁴ and Bluetooth navigation systems is the same as for RFID Location Systems. The radio sources with unique identification are placed at known location and a receiver senses proximity to these sources. In the signpost concept, the position of the nearest radio source is adopted for the receiver. In the wave based concept, the position is calculated based on the distance determination to the radio sources. The distance can be determined either by signal travel time measurement or by signal strength measurement. One of the first systems based on these principles was Place Lab developed by Intel (LaMarca et. al 2005). The Place Lab architecture consists of three key elements: Radio beacons in the environment, databases that hold information about beacons' locations, and the Place Lab clients that use this data to estimate their current location. There is similar software developed by company Navizon (<http://www.navizon.com/>), which offers software for wireless positioning that can be installed in hand held computers (PDA) or in mobile telephones. There are also systems that make use of signal strength to derive the distance to the radio source. For example system RADAR developed by Microsoft research (Bahl and Padmanabhan 2000) uses signal strength information gathered at multiple receiver locations to triangulate the user's coordinates. Triangulation is done using both empirically-determined and theoretically computed signal strength information. Similar approach is used in Roos et al. (2002).

Infrastructure: WiFi access points, stationary blue tooth devices, GSM base stations, database of locations (coordinates) of the above mentioned radio sources.

The database can be filled in different ways. The most obvious way is to obtain access point locations from their owners or by explicit mapping, i.e. determination of position of the source by some positioning technique. The other possibility is so called "war driving". War-driving is the act of driving around with a mobile computer equipped with a GPS device and a radio (typically an 802.11 card but sometimes a GSM phone or Bluetooth device) in order to collect a trace of network availability. War-driving has become hobby for many radio enthusiasts and groups of war-drivers have formed online and offline clubs to share and pool their trace data. Each war-driving trace is a time-coded sequence of records containing the latitude and longitude of where the record was taken, as well as the list of radio sources and associates signal strengths that could be heard at that time. By pooling their war drives together and applying some simple averaging, these groups have produced estimated locations for millions of beacons. Public domain war-driving software has been developed for most computing platforms, and there are many aggregation websites to which war-

⁴ Wireless Local Area Network

drives can be submitted. Since the positions of beacons are being inferred from observations tied to GPS estimates, war-driving databases only contain estimates of beacons' positions. The error in these estimates translates into a decrease in the accuracy of location estimates made by Place Lab, RADAR or similar systems. As an example, wigo.net is the largest of the 802.11 war-driving repositories, and contains over 17 million known access point positions - Figure 10.

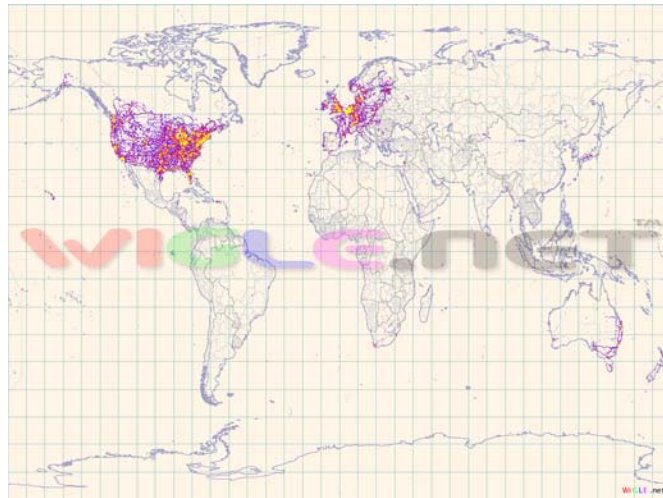


Figure 10. Location of wireless network from wigo.net

Accuracy: medium

LaMarca et al. (2005) reports accuracy 13 – 22 m in experiments performed in different environments – urban, suburban, and residential.

Coverage: local

The coverage of WiFi access points (802.11) is very high in populated area and almost zero in rural areas. LaMarca et al. (2005) determined experimentally accuracy and coverage in different environments - Table 2.

Table 2. Accuracy and coverage for WLAN and GSM based location systems.

	802.11		GSM		802.11 + GSM	
	accuracy	coverage	accuracy	coverage	accuracy	coverage
Downtown Seattle (Urban)	20.5 m	100.0%	107.2 m	100.0%	21.8 m	100.0%
Ravenna (Residential)	13.5 m	90.6%	161.4 m	100.0%	13.4 m	100.0%
Kirkland (Suburban)	22.6 m	42.0%	216.2 m	99.7%	31.3 m	100.0%

Integrity: no integrity monitoring

Reliability: less than 100%

Update rate: less than 1 Hz

3.9 Inertial navigation system

Class: Dead reckoning system

Inertial techniques are based on the simple principle that the position of the body can be determined by a double integration of the acceleration and a single integration of angular velocity, when measured in a known reference frame. Inertial positioning is the application of these techniques to positioning. The models used are based on classical mechanics, employing Newton's universal law of gravitation and Hooke's law. In most of the applications of inertial navigation the measuring unit consists of three accelerometers and three gyroscopes, sensing acceleration and angular velocity, respectively. The block of sensors together with a timing device is called the Inertial Measuring Unit (IMU). In order to apply the basic principle for the fixing of positions on the earth, it is necessary to mechanize a measurement frame with known orientation in respect to an inertial reference frame. In this system three accelerometers can be used to measure the three components of acceleration. The physical arrangement of the inertial sensors relative to the vehicle and relative to coordinate frames is usually called *inertial platform* or *mechanization*, which is basically a stable element on which three mutually orthogonal accelerometers and three gyroscopes are mounted. There are two general types of mechanization: the stabilized and strapdown. Stabilized platforms provide angular motion isolation from the vehicle; while

strapdown systems are just what the name implies: the platform holding the IMU's is attached firmly to the vehicle. In the stabilized system, the platform consists of a stable element that is connected to the vehicle through a set of gimbals, each allowing rotation about a particular axis. To a large extent, the isolation could be achieved by the gimbals themselves and the inertia of the stable element (like a hammock in a ship on gently rolling waves), but the bearings are not absolutely frictionless and the stabilization is better controlled by purposely creating appropriate rotations about the gimbal axes using servomotors. The amount of rotation needed to isolate the platform from the vehicle motion is obtained from the output of the gyros mounted on the stable element.

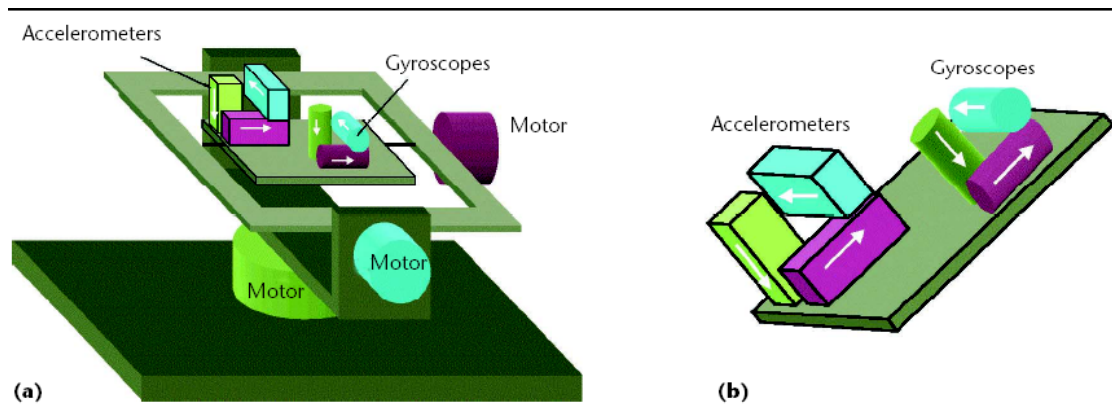


Figure 11. Inertial Measurement Units: (a) gimballed (b) strapdown. (Welch G. and Foxlin E. 2002).

In the strapdown mode, the accelerometers and gyros are physically bolted to the vehicle (possibly, with some shock/vibration isolation mounts), where all instruments are contained within a single box. Consequently, these sensors are subjected to the entire range of dynamics of the vehicle, which degrades their performance.

The main advantage of strapdown systems is smaller size, weight, and power consumption, and lower cost (there are no mechanically complex set of gimbals as in the stabilized system). Though the highest accuracy of a strapdown system is worse than that of the best stabilized system, the recent technological developments in optical and MEMS (Micro-Electro-Mechanical Systems) gyroscopes have brought the strapdown system close to gimballed ones. With virtually no moving parts, the strapdown system based on optical gyros is also far superior in maintenance and in the mean time between failures. Being also much less expensive, the latter has the greater potential for city navigation application.

The main problem with inertial navigation, as well as with other dead reckoning systems is rapid accuracy deterioration in time. Inertial navigation keeps high accuracy only for several minutes (or tens of minutes for the most precise instruments). Then, in long run, the INS

can preserve low horizontal accuracy, but vertical accuracy deteriorates unbounded (Jekili 2001). For this reason, the INS is usually combined with some other sensors, like GPS, radar, odometer, etc, which provide information needed to correct the state vector computed by INS. There are several such products available on the market. The most common combination is GPS and INS, which is used in military applications, as well as in mobile mapping systems for determination of position and orientation of mapping sensors (cameras, laser scanners). Low cost GPS/INS instrument costs from about 4 000 USD and it can deliver metre level positional accuracy and 0.1° accuracy of orientation angles (Elkaim et al. 2008). Figure 12 shows an example of GPS/INS instrument.



Figure 12. MMQ-G GPS/INS instrument by Systron Donner Inertial (<http://www.systron.com/>)

The INS navigation can also be supported by so called zero velocity update (ZVUP), i.e. if the INS is standing still, the velocity is known to be zero. Godha and Lachapelle (2008) describe development of GPS/INS navigation system for pedestrians. They attached a small low-cost inertial measurement unit to a shoe - Figure 13. The fact that the foot comes to rest (i.e. velocity is 0) every time it strikes the ground can effectively be used as ZVUP.



Figure 13. Foot mounted inertial sensor. (Godha and Lachapelle 2008)

Infrastructure: no infrastructure required

Accuracy: low for long term standalone navigation, high – medium when combined with other sensors.

Capacity: unlimited

Availability: 100 %

Coverage: global

INS is an autonomous system, it can be used anywhere

Integrity: depends on the particular instrument, monitoring is possible

Reliability: depends on quality of sensors, usually close to 100%

Update rate: 100 Hz – 1 000 Hz

Almost all instruments, even low-cost, provide at least 100 Hz update rate. More advanced (also more expensive) are able to work up to 1 000 Hz rate.

4 Conclusions

In this report we analysed different navigation methods that are potentially suitable for city navigation, i.e. personal navigation in urban and indoor areas. According to the positioning principle, we divided the navigation systems into three classes: signpost, wave based and dead reckoning systems. According to the place where the position of user is computed, we divided the navigation systems into self-positioning and remote positioning systems. Self-positioning systems are more suitable for city navigation. Remote positioning systems are better suited for tracking and monitoring applications. Each system was assigned with the following quality parameters: accuracy, availability, capacity, continuity, coverage, dimension, integrity, reliability and update rate. Our goal was to identify the most suitable methods based on the quality parameters and required infrastructure. The accuracy is one of the most important quality parameters for city navigation. To be able to locate addresses, identify correctly position on dense street networks, to find shops or offices inside buildings, high accuracy (better than 10 m) is required. Availability of city navigation systems mostly depends on the technical capabilities of the infrastructure. Today most of the systems have almost 100% availability. Capacity of a navigation system is usually unlimited for self-positioning systems, so it is not a problematic issue for city navigation systems. Continuity, integrity and reliability are very important parameters for navigation systems for machine guidance, but not so critical for personal city navigation, since eventual failure of the navigation system does not cause any direct danger in the latter case. Coverage, together with accuracy is the most important parameter. The requirement of city navigation is that the system covers all areas in the city, including narrow streets, indoor and underground areas. Another requirement for a city navigation system is that it should be able to update the position of user as he/she moves. Update rate in term of number of position determination per second is not as important as the ability to update position if user changes position by some distance.

As we could see in chapter 3, there are many existing navigation systems with already built infrastructure. The most popular are global navigation satellite systems, today GPS operated by USA and Russian GLONASS, in the future European Galileo and Chinese Compass/Beidou. GNSS fulfil almost all requirements for city navigation; they are accurate, with global coverage, unlimited number of users with high availability and reliability. They have just one shortage: weak signal, which is unusable in obstructed areas. The best solution to overcome this problem is to install additional satellite-like transmitters – pseudolites. The pseudolites can extend the use of GNSS into indoor environments. The main disadvantage is high cost of the pseudolites, which provide coverage for relatively small area. Another disadvantage is the necessity of modification of existing GPS receivers.

Terrestrial radio navigation systems for aviation and maritime use is another group of existing navigation systems with built infrastructure. Although these systems were designed for aviation and maritime use, it is possible to use some of them (Loran C and Chayka) also

on land. However, because of low accuracy (400 – 500 m) they are not suitable for city navigation.

Today almost all cities in the world have dense networks for cellular communication. Nodes of these networks are base stations, which enable two-way communication with mobile units (mobile phones). Cellular communication networks can also be used for positioning of mobile stations. The main advantage of cellular telephone positioning systems is already built infrastructure with many users equipped with mobile phones. Disadvantage is low accuracy (hundreds of metres) of simple positioning methods that can be used by unmodified mobile phones. There are more accurate methods based on signal strength determination (fingerprinting), but extensive database with location of known signal strength is required. To achieve more accurate mobile phone positioning, more advanced method (EOTD) must be used, but this method requires modification of cellular hardware and additional hardware – so called location measurement units. This method is not widely deployed yet.

Similar positioning principles used for cellular network navigation can be applied on Bluetooth and WLAN – wireless local area network, with WiFi access points (also called 802.11) as nodes.

Another possibility of solving city navigation is to create new specialised infrastructure for navigation. In our report we mentioned two remote positioning systems: The Active Badge and The Active Bat. Both systems are designed for monitoring of personnel in office environment. The position of users is computed at a central server, so these systems are not suitable for city navigation. There are also self-positioning navigation systems (for example Cricket) working on similar principle as the Active Bat or Active Badge, which are suitable for city navigation. Specialised combined radio/ultrasonic beacons must be placed in the areas to be covered and the users must wear specialised receivers – positioning devices.

In our opinion, the most promising technology for city navigation infrastructure is RFID (radio-frequency identification). Inexpensive passive RFID tags are able to transmit their position to the users that pass by. The advantage of passive RFID tags is their cost – just a few cents per piece, their virtually unlimited duration without necessity of maintenance. This makes possible to establish very dense network of reference tags covering the areas of interest.

So what is our recommendation for an ideal city navigation system? As we could see, each individual navigation method has some disadvantages, or weak sides. In our opinion, only combination of different methods and sensors can create “perfect” navigation system. Therefore different kind of navigation infrastructure should be available in the cities. Therefore we recommend utilising existing radio sources (WiFi access points, stationary Bluetooth devices and GSM base stations) that can be used for navigation and to create and maintain the database with their positions. Then we recommend installing new infrastructure – passive RFID tags on pre surveyed locations. They should be installed in areas with insufficient coverage of existing radio sources and in areas where higher accuracy is required, for example shopping centres, train or subway stations, etc.

Such infrastructure (radio sources and database with their location) would be a solid base for development of navigation devices based on different combination of sensors.

5 References

- Bahl P., and Padmanabhan V.N. (2000). RADAR: An In-Building RF-based User Location and Tracking System. IEEE Infocom 2000, Tel Aviv, Israel.
- Beser J., Parkinson B.W. (1982). The application of NAVSTAR differential GPS in the civilian community, *Navigation*, 29(2): 107-136.
- Brown R.G. (1996). Receiver autonomous integrity monitoring. In: Parkinson B.W., Spilker J.J. (eds): *Global Positioning System – theory and applications*, vol 2. American Institute of Aeronautics and Astronautics, Washington DC: 143 – 165.
- Binghao Li, Mumford P., Dempster A. G. and Rizos C. (2009). *Secure User Plane Location: concept and performance*. GPS Solutions. Springer Berlin / Heidelberg. On line publication.
- Brown D.,E., (2007) *RFID implementation*. McGraw Hill, New York.
- Cook D., Sajal D. *Smart Environments (2004). Technology, Protocols and Applications*. John Wiley & Sons, Incorporated, Hoboken, New Jersey.
- Drane C., Rizos C, (1998). *Positioning systems in intelligent transportation systems*. Artech House, Boston, London. ISBN: 0-89006-536-5
- Department of Defense (1995). *Global Positioning System standard positioning service signal specification*. 2nd edition.
- Department of Defense (2001). *Global Positioning System standard positioning service performance standard*. Available from the U.S. Assistant for GPS, Positioning and Navigation, Defense Pentagon, Washington DC.
- Elkaim, G.H., Lizarraga, M., Pedersen, L (2008). Comparison of low-cost GPS/INS sensors for Autonomous Vehicle applications. In: *Position, Location and Navigation Symposium, 2008 IEEE/ION*, pp 1133-1144.
- Godha S., and Lachapelle G., (2008) Foot mounted inertial system for pedestrian navigation. *Measurement Science And Technology* 19 075202.
- Grafarend E.W., Krümm F.W. (2006). *Map Projections: Cartographic Information Systems*. Springer. ISBN: 3540367012.
- Harrington R.L., Dolloff J.T. (1976). The inverted range: GPS user test facility, *IEEE PLANS'76*, San Diego, California, 1-3 Nov., 204-211.
- Harter A., Hopper A., Steggle P., Ward A. and Webster P. (1999). The Anatomy of a Context-Aware Application. In: *Proceedings of the 5th annual ACM/IEEE international conference on Mobile computing and networking*. Seattle, Washington, United States.
- Hofmann-Wellenhof B., Lichtenegger H. and Collins J. (1997). *GPS, Theory and Practice*. Springer Verlag, Wien, New York
- Hofmann-Wellenhof, Legat, Wieser (2003). *Navigation. Principles of positioning and guidance*. Springer-verlag, Wien, New York.

- Jekeli, Ch. (2001). Inertial Navigation Systems with Geodetic Applications. Walter de Gruyter, Berlin, New York.
- Klein D., Parkinson B.W. (1986). The use of pseudo-satellites for improving GPS performance, Global Positioning System (red book), Vol III, Institute of Navigation, 1986, 135-146.
- Lakmali B.D.S., Dias D. (2008). Database Correlation for GSM Location in Outdoor & Indoor Environments. 4th International Conference on Information and Automation for Sustainability (ICIAFS 08), Colombo, Sri Lanka.
- LaMance J, Jarvinen J, DeSalas J (2002). Assisted GPS: a low infrastructure approach. GPS World, March 1
- LaMarca A., Chawathe Y., Consolvo S., Hightower J., Smith I., Scott J., Sohn T., Howard J., Hughes J, Potter F., Tabert J, Powledge P, Borriello G, Schilit B. (2005). Place Lab: Device Positioning Using Radio Beacons in the Wild. In: Proceedings of Pervasive 2005, Munich, Germany.
- Leick A, (2004), GPS Satellite Surveying, Third Edition, John Wiley & Sons, ISBN 0-471-05930-7.
- Longfoot, J. (1991). An automatic network travel time system—ANTTS. In: Vehicle Navigation and Information Systems Conference, 1991.
- Miller L., E., (2006). Indoor Navigation for First Responders: A Feasibility Study. Wireless Communication Technologies Group Advanced Networking Technologies Division Information Technology Laboratory. http://www.antd.nist.gov/wctg/RFID/Report_indoornav_060210.pdf
- National Institute of Standards and Technology
- Moritz H., Mueller I.I. (1987). Earth rotation - theory and observation. The Ungar Publ. Company, New York.
- MacGougan G., Lachapelle G., Klukas R., Siu K., Garin L., Shewfelt J. and Cox G. (2002). Performance analysis of a stand-alone high-sensitivity receiver. GPS Solutions. Springer Berlin / Heidelberg. Volume 6, Number 3, pp 179-195.
- Ni L.M., Liu Y. Lau Y.C., Patil A.P., (2004). LANDMARC: Indoor Location Sensing Using Active RFID. ACM Wireless Networks, (WINET), Volume 10, Issue 6, pp 701–710.
- Otsason V., Varshavsky A., LaMarca A. and de Lara E. (2005). Accurate GSM Indoor Localization. In Proceedings of Ubicomp 2005, Tokyo, Japan.
- Priyantha N., Miu A., Balakrishnan H. and Teller S., (2001). The Cricket Compass for Context-Aware Mobile Applications. ACM Mobile Computing and Networking, pp. 32 – 43.
- Ramm K., Czommer R. and Schwieger V. (2005). Map-based Positioning using Mobile Phones. In: XXIII FIG Congress, Munich, Germany.
- Rizos C., (2005). Pseudolite Augmentation of GPS. School of Surveying & Spatial Information Systems, University of New South Wales, Sydney. Download: http://www.gmat.unsw.edu.au/snap/publications/rizos_2005a.pdf

- Roos T., Myllymäki P., Tirri H., Misikangas P., Sievänen J. (2002). A Probabilistic Approach to WLAN User Location Estimation. *International Journal of Wireless Information Networks*, Vol. 9, No. 3, pp 155 – 164.
- Van Dierendonck A.J, Fenton P., Hegarty C., (1999). Proposed Airport Pseudolite Signal Specification for GPS Precision Approach Local Area Augmentation Systems. Technical paper available at www.novatel.com.
- Want R., Hopper A., Falcao V., Gibbons J. (1992). The Active Badge Location System. *ACM Transactions on Information Systems*, Vol. 10, No. 1, pp 91-102.
- Zandbergen P.A. Accuracy of iPhone Locations (2009). A Comparison of Assisted GPS, WiFi and Cellular Positioning. *Transactions in GIS*, Volume 13, Issue s1, pp. 5 – 25