Cooperative PNT: PNT Sensors and Techniques

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ABSTRACT

In this paper navigation systems and sensors that can be used in a cooperative navigation system are introduced. A general grouping of navigation systems is given to better understand navigation system different characteristics, advantages, and disadvantages with respect to each other.

Common navigation systems are explained shortly together with their main idea, difference from navigation point of view. Sensors that can be used together with navigation system, and why they are used are also given to provide user with a wide range of navigation possibilities.

1.0 NAVIGATION SYSTEMS

Before getting into the topic, let us try to understand what we mean by navigation and what types are there. It is defined as "the process or activity of accurately ascertaining one's position and planning and following a route". We can start by dividing a main branch off, we will not take into account cases where you know just enough information about your target so you can follow it, reach to it, these cases are generally guidance problems and even though they form a subset of navigation problems we will not consider them as navigation in this presentation.

After we separate guidance cases, the remaining navigation problems require you to know your platform's position, attitude, and other information with respect to a reference commonly referred as coordinate frame or frame. This frame can be an absolute one or a time varying one. While a platforms position, attitude etc. wrt. a coordinate frame can be considered an information, this can be misleading. In general navigation is not an information provided to the platform from outside (even though it is possible to find such applications they are generally rare and harder to implement cases) but it is a series of measurements done by the platform and a set of calculations using these measurements. So, in almost all cases of navigation, platform needs to have several sensors that can do the measurements and then a calculation capability to use these measurements to find the solution itself. In general, if a third part needs the platforms navigation information navigation information obtained on the platform needs to be transferred to the third party by some separate communication system.

Let us try to categorize navigation systems on how they work, which will let us understand what they need, when do they perform best and when they do not, and what more do we need to design better navigation systems. Categorizing navigation systems turns out to be much more complicated problem then it looks. Making a few searches on internet will show you quickly people understand very different things from a simple word like navigation. Then everybody will start dividing systems they know into a few categories. This creates a one sighted view of the area and need for new categories as new systems discovered. When we wrote a simple navigation booklet back in 2002 facing these difficulties, we divided navigation systems into three categories depending on the source of information they use. They are:

1) Database matching techniques
2) Externally dependent systems
3) Dead reckoning systems

Let us try to understand each category one by one.

1.1 Database Matching Techniques

In these navigation techniques user needs a list or a database of know objects and their corresponding coordinates. These can be given as a printed map or a computer file or any other convenient form. These map or database points needs to be measured, checked, corrected, and prepared in the correct format at an earlier time and entered into the platform memory in usable format. On the day (instant) of navigation platform 'looks' (can be visual, IR, Radar or any other means) and 'sees' (recognizes) one or more objects that area available in the 'map'. Platform measures distances, and or angles to the recognized objects and computes its own position using known positions of objects and its distance, angle from these known objects.

If we summarize, in a map-matching navigation systems you need:

1) A database of points of interest with known coordinates
2) An ability to observe (see) the points of interest from the platform
3) An ability to calculate relative position to the points of interest
4) An ability to match observed points of interest to known points of interest
5) An ability to perform necessary calculations to compute the platforms own coordinates

Please note that even the algorithms matching whole pictures with pictures, even if they are using new techniques such as Artificial Intelligence are measuring or computing angles and distances to known points of interest even if they do not say explicitly and are still in this group of systems. All navigation systems that use natural phenomena, such as landscape features, star maps, gravity variations, landscape heights, sea bottom depts etc. will be in this category.

Know let us try to use the advantage of clustering these navigation systems in this group. For these navigation systems to work you need:

1) A map (or database of a priori information)
2) A way to observe objects of interest
3) A way to compute your position (processing power and an algorithm)

If any of these are missing – you do not have a map of the area we will navigate, it is foggy today and you cannot see, or your computer is not working or not fast enough you will not be able to get navigation results. Your navigation accuracy will depend on

- Accuracy of your map – database
  - How many points of interest you have
  - How accurate is the information you have about these points
  - How recent is the information collected
- A way to observe objects of interest
  - Can you observe and identify them correctly

    - How many points you can observe and identify simultaneously
    - How frequently you can update your observations
- A way to compute your position
    - How accurate is your angle/distance measurements to the identified points
    - How accurate is your relative position computation/estimation algorithm
    - How fast your code can provide results

1.2 Externally Dependent Systems

In these navigation techniques user builds a set of external references himself to take the place of natural points of interest. Since User builds these he knows exact location of these infrastructure eliminating the need to collect one of the information required. This infrastructure is built to facilitate the measurement of distance, angle, or both from the platform to the build infrastructure to make the second step, measurement much easier. All man made navigation systems from Loran to GNSS systems fall into this category.

Navigation systems in this category will have

1) A network of stations at known locations (infrastructure)
2) A way to communicate with this network of stations and measure distance and/or angle
3) A way to compute your position using measurements and known positions of stations

Please note that all man-made navigation systems will fall ‘into this category from the simplest to the most complicated. Even if you are using complicated Artificial Intelligence algorithms and not measuring individual distances or angles one by one the system is still considered in this category since it still shares almost all advantages and disadvantages of the category which are:

1) An infrastructure (a network of stations at known points – not necessarily stationary)
2) A way to talk to the infrastructure (communicate with infrastructure to facilitate distance and or angle measurement – historically RF but not necessarily)
3) A way to compute your position using measurements and known points (processing power)

If any of these are missing – you are in enemy territory and infrastructure is not compatible or not working, you cannot communicate with the stations – related frequencies are being jammed, or your computer is not working you will not be able to get navigation results. Your navigation accuracy will depend on

- Your infrastructure
    - How many stations you have around your navigation path
    - How accurate is the information you have about these stations
    - How up to date the information is and especially if your stations are not stationary)
- Your measurement system
    - Can you receive related signals (not jammed or spoofed)
    - How accurately you can measure distance/angle from station
    - How frequently you can update your measurements

- Your computing capability
  - How accurate is your angle/distance measurements to the identified stations
  - How accurate is your relative position computation/estimation algorithm
  - How fast your code can provide results

1.3 Dead Reckoning Systems

Dead reckoning is the process of calculating current position by using previously determined reference position (starting point) and advancing that position based upon measured speeds over elapsed time and attitude (course). In other terms, it is computing how much a platform (historically ship) moved by measuring speed and direction of movement since last update and adding it to the position of the last update.

A dead reckoning navigation system will need these parts/information to work.

1) A given starting position and orientation (infrastructure)
2) A way to measure direction and speed (rotation and acceleration)
3) A way to measure time (needed for integration)
4) A way to compute your position using measurements and known previous position

A dead reckoning navigation system will compute how much the platform moved in position and in direction and simply add it to the last know position updating the known position and then repeat the same process. Since it adds up new calculations to the old known position and there is no other new direct position information, errors can grow unboundedly with passing time. It was the main navigation system used in long haul open sea voyages and was open to huge errors. By the invent of gyroscopes and accelerometers and with the race of intercontinental ballistic missiles, it became possible to produce extremely accurate sensors, with the invent of computers the accuracy and frequency of computations are increased immensely and today systems that can update position and attitude 1000 times a second and provide accuracies up to 1 nm error every 6 months are possible (even though they are very costly (expensive, big, power hungry) and hard to reach (military secret protected in every country and also protected by international law).

If we reiterate a dead reckoning system needs

1) A known starting position
2) A way to measure direction and speed (rotation and acceleration)
3) A way to measure time accurately
4) A way to compute your position using measurements and known point (processing power)

Please note that this time the information needed is totally internal other than the starting point. This navigation system does not require outside information (to see objects of interest or talk to infrastructure stations) so it is almost impossible for enemy to confuse or deny this type of navigation. On the other hand, its errors can grow unboundedly with passing time and unless you are using an expensive (as weight, power size and price) system in a big platform you may run into trouble.

Your accuracy depends on

- Your initial starting position accuracy
  - Your position accuracy
  - Your attitude (direction) accuracy – high performance systems compute themselves

- Your measurement accuracy
  - How accurate are your measurements
  - How frequently you can update your measurements
- Your computing capability
  - How accurate is your computational accuracy (how small numbers can be)
  - How frequently you can do the necessary computations

2.0 DATABASE MATCHING TECHNIQUES

This technique involves sensing the surrounding environment, comparing this to a pre-stored representation of that environment, and deducing a sensor location and orientation from that comparison. Some versions of this type of navigation are given below. This is by no means a complete list and just intended to give a few examples of what is possible.

2.1 Map Matching

Map matching is probably one of the oldest navigation techniques used by man. If you have a map that was previously generated and if you can see and recognize any of the object shown on map (landmarks, streets, rivers etc.) and if you can measure or estimate where you are relative to that object you can easily figure out where are you approximately located on that map.

While understanding how to use a paper map can be very easy, using an electronic map with features, using cameras to make observations automatically and measuring distances electronically makes much more faster and accurate navigation systems.

2.2 Image Matching

When using camera captured images and computerized algorithms, the position and orientation of the camera can be estimated from a single frame by maximizing the correlation between the observed image and an image database. Even though, no object is recognized one by one and no measurement to that object is calculated but the job done effectively correspond to that of map matching.

If only a sparse 3D point or line model database of the area is given, and current camera position and attitude is determined from several known points/lines this is called Spatial Resectioning.

2.3 Laser Imaging

A Laser imaging system traditionally uses a scanning laser diode to measure the ranges to all nearby reflecting surfaces. The resulting laser point cloud is an ‘image’ of the surrounding area. If the objects in this point cloud can be matched to the points in an existing database then very precise navigation information may be calculated since range measurements from laser imaging systems can be very precise. A point to mention is while in camera based systems it is easier to match features such as corners in laser based systems it is easier to match surfaces.

2.4 Terrain Referenced Navigation

Terrain Referenced Navigation (TRN) is the name for a group of techniques using sensed terrain height (or depth) information and a terrain database to generate position measurements first developed for use in cruise missiles.

A radar altimeter is used to measure the distance between the platform and the terrain. A barometric altimeter can be used to learn the absolute altitude of the platform compared to sea level. The difference between these two measurements is the height of the terrain platform is flying over. If there are enough measurements over a period of time and if a digital elevation map of enough accuracy and frequency exits a comparison of elevation values measured in sequence can produce a location and direction. The guidance system can then use this information to correct the flight path of the platform if necessary. In general, during the cruise portion of the flight to the target, the accuracy of the system has to be enough only to avoid terrain features. This allows the maps to be a relatively low resolution in these areas while portion of the map for the terminal approach has to be higher resolution. While these techniques are used to minimize computer power and storage requirements considerable advances in both areas, sometimes makes such conservation techniques unnecessary.

In general, TRN systems are attractive in times of GPS data unavailability especially over unfriendly areas as they are virtually impossible to jam, and they operate autonomously (i.e., they do not require on external systems).

2.5 Celestial Navigation

Historically celestial navigation is the process of finding one's geographic latitude and longitude by means of angular measurements between a celestial body (e.g., the Sun, the Moon, a planet, or a star) and the visible horizon, with knowledge of the correct time.

Modern celestial navigation systems are able to simultaneously track many stars, thus allowing constellation matching (using an appropriate embedded star catalogue database) which, in turn, improves the accuracy, continuity and robustness of the navigation solution. Celestial navigation systems are self-contained, provide worldwide operation, and cannot be jammed. However, cloud cover and other obstructions of the sky may preclude their use. They will require an accurate clock as the earth is rotating around itself. Angle measurements on the order of 1 to 2 arc seconds are achievable which corresponds to a positioning accuracy of about 50 to 100m on sea level.

2.6 Gravimetry

Gravimetry is the measurement of the strength of a gravitational field. A gravity gradiometer measures the gradient of gravity i.e., the variation of gravity with distance. By comparing the measured gravity gradient with a database, the location of the gradiometer (platform) can be inferred.

Gradiometer navigation has the tactical advantage of being a passive system and is thus stealthy. Unlike established terrain referenced navigation systems, it may also be used over sea and flat featureless terrain. Exploitation of measured gravity gradients may be useful in subterranean applications. However, the granularity of available global gravity maps is coarse, and the results are not especially accurate. Local gravity maps may be required for high accuracy results as well as a sufficiently sensitive sensor (gravity gradiometer).

3.0 EXTERNALLY DEPENDENT SYSTEMS

Externally Dependent Systems are generally man-made systems that require a pre-installed infrastructure. Typically, the system would receive radio signals from the infrastructure, and based on any number of techniques, determine its position. In this text we will give a few examples to highlight where these systems excel and where they have short comings.

3.1 Long Range Navigation (LORAN)

Long **Ra**nge **N**avigation (LoRaN) system started to be designed during in World War II and became a standard system all around the world in 1950's for long distance air and sea navigation. Maximum usable range was 1,000 miles (1,600 km) over land and 1,500 miles (2,400 km) on the sea, with typical accuracies of 150 to 300 meters.

The system used Time Difference of Arrival technique to be able to accurately determine range without any need for the transmitter (infrastructure at land) and platform (air or sea vehicle). A pair of towers with sufficient distance between them pinged at the same time. If the user receiving these pings hear them at the same instance, user must be equidistant from both towers, so it must be located on the perpendicular line that crosses the base line that connects two stations. If user receives first towers signal 1 ms before the other one, user can calculate the points where he can be in, and those points will be defined by a parabola. If you repeat the same process from a second pair of towers, you will obtain 2 sets of parabolas where they will intersect in one point which is the user's location. While this system required big antennas that transmit relatively low frequency signals (MHz) in high power user equipment kept at minimum. User equipment needed to receive radio signals and measure (or display) time difference between signals and have a list of tower pairs, their locations, and frequencies. Most importantly system required no clock synchronization between the transmitting towers and user equipment which could be extremely challenging even today.

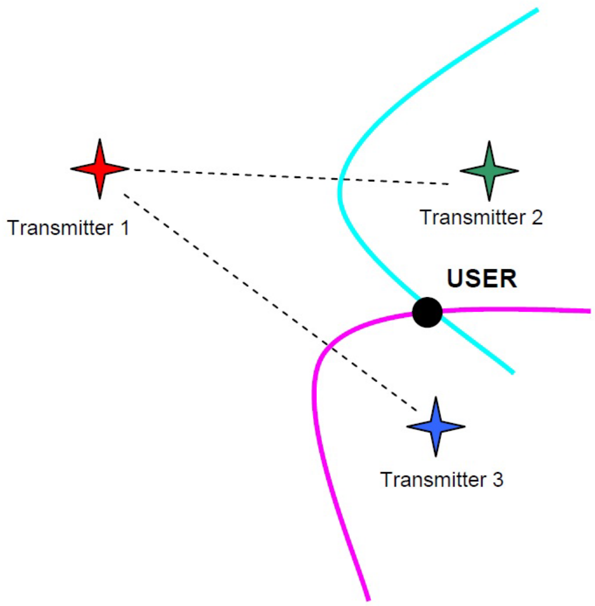

Figure 1: A Loran-C user position is at the intersection of hyperbolic lines of position which result from the time difference of arrival of pulses from pairs of transmitter stations (1&2 and 1&3).

3.2 Distance Measuring Equipment (DME)

Distance Measuring Equipment (DME) stations for aircraft navigation were developed in the late 1950's and are still in world-wide use as a primary navigation aid. The aircraft sends a series of pulse-pairs, and, after a precise time delay (typically 50 microseconds), the ground station replies with an identical sequence of pulse-pairs. The DME receiver in the aircraft searches for reply pulse-pairs with the correct interval and reply pattern to its original pattern. The user's receiving equipment measures the total round trip time – 50 microseconds divided by 2 multiplied by speed of light gives the slant range between the user aircraft and the DME station. Typical accuracy of a DME station is around 185 meters.

As in Loran systems, user equipment is very simple, a radio transmitter and receiver and a simple stand alone clock that does not need to be synchronized to any other clock. User have to have a direct line of sight and have to be able to find its altitude independently. System currently in use in almost every civil airport.

3.3 VHF Omni Directional Radio-Range (VOR) System Pulse Pair

The VHF Omni Directional Radio-range (VOR) system is comprised of a series of ground-based beacons operating in the VHF band (108 to 118 MHz). A VOR station transmits a reference carrier frequency modulated (FM) with a 30 Hz signal from the main antenna. An amplitude modulated (AM) carrier is electrically swept around several smaller antennas surrounding the main antenna. This rotating pattern creates a 30 Hz Doppler effect on the receiver. The phase difference of the two 30 Hz signals gives the user's azimuth with respect to the North from the VOR site. User equipment tuned into this signal will receive two sets of signals and the phase difference between them give the user it is angle to the VoR station. The bearing measurement accuracy of a VOR system is typically on the order of 2 degrees, with a range that extends from 25 to 130 miles.

As in previous cases, while the VoR station and its antennas (infrastructure) is complicated and expensive, user equipment is very simple, a radio receiver and a simple circuitry to measure phase difference is needed. As before, user have to have a direct line of sight. System currently in use in almost every civil airport, but some countries starting to phase them out as GPS systems become more reliable.

3.4 Tactical Air Navigation System (TACAN)

TACAN (Tactical Air Navigation) is an enhanced VOR/DME system designed for military applications. The VOR component of TACAN, which operates in the UHF spectrum, makes use of a two-frequency principle, enabling higher bearing accuracies than civil version. The DME component of TACAN operates with the same specifications as civil DME as explained above. The accuracy of the azimuth component is about ±1 degree, while the accuracy of the DME portion is ±0.1 nautical miles.

As in civilian systems, it provides the user with bearing and slant-range distance. It can also be used on ships to provide bearing and slant range information to ship to enable aircraft, helicopter landings to ships

3.5 Global Navigation Satellite System (GNSS)

Global Navigation Systems revolutionized the navigation systems and obtained domination almost in every application. We wouldn't even need to mention another navigation system if it weren't for the major shortcomings of the systems.

User equipment makes a pseudo range calculation using satellite transmission (which is tagged by a precise atomic clock) and its own clock using Time of Arrival (how much time it took for the satellite signal to reach user equipment). Since the user clock is not synchronized with atomic clocks in the satellites, this is not a correct measurement. But each satellite's atomic clock is synchronized with each other and if one makes four such measurements one can solve for four unknows, user's latitude, longitude, altitude, and user clocks bias with respect to satellite atomic clock.

Satellite navigation provides a great number of advantages: It provides global coverage, at all times of the day and in all weather; it is very accurate (positions to a few meters, velocity to 0.1m/s, time to a few microseconds or better); there is no error growth with time; and the user requires only a small, low-cost receiver. However, there are some significant limitations as well: it is dependent on external signals which may be jammed or blocked by buildings, terrain, and foliage; there may be position shifts due to changing satellite visibility; and there may be no signal validation (open to spoofing) or real time integrity monitoring.

3.6 Pseudolites

A pseudolite (pseudo-satellite) is a ground-based transmitter that is capable of transmitting navigation signals that mimic satellite navigation systems. They can be used to augment GNSS satellite signals where there may be significant satellite shading effects, such as indoors.

In order to utilize pseudolites with a GNSS, the signals must be time synchronized with GNSS time, the location of the pseudolites must be known, and the transmitted signals must be of compatible power levels.

If one assumes that the receiver uses only pseudolite signals, the transmitted signal power can be changed at will to penetrate difficult environments and to improve antijamming performance of the system. For best performance, the pseudolites should be placed around the area of interest to provide good geometry, and therefore good accuracy.

3.7 Ultra-Wideband (UWB)

Ultra-wideband (UWB) signals are produced by generating and transmitting short pulses of RF energy (on the order of nanoseconds and less). Such short pulse durations in the time domain result in a very wide bandwidth in the frequency domain. Because of this short pulse duration, very high range resolution is possible.

Positioning with UWB technology can be accomplished by measuring the Time of Arrival (TOA) if there is a synchronous clock between the nodes. If a synchronous clock does not exist then two way ranging (similar to a DME system) can be used. A number of UWB systems have demonstrated indoor positioning with errors of less than 1m for ranges up to 500m. However, positioning accuracy will depend on the geometry of the beacons and the obstacles between the transmitter and receiver.

3.8 Signals of Opportunity (Radio / TV Broadcast Signals)

The use of Radio or TV broadcast signals can be used to provide a user’s position. By measuring differences in the times at which the broadcast signals arrive at a user’s location and at a second receiver at a known fixed location, an estimate of the ranges between the user and the transmitters can be determined. If you can calculate 3 or more such ranges it might be possible to calculate user’s position. Note that this will require additional communication (if not synchronization) between the reference station and user equipment.

The exploitation of such signals comes with several advantages. No deployment of a transmitter network is required (it is already available), and the high power, relatively low frequency signals penetrate buildings well and are less susceptible to multipath. However, the concept can only be employed in areas in which there are known operating TV or radio broadcast stations in necessary numbers, and they are transmitting from different and suitable positions (In most cities all radio stations broadcast from one tower making them effectively a single source).

3.9 Mobile Telephone Positioning

Positioning information can be obtained from mobile telephone systems. Either the Time Difference of Arrival (TDOA) or Time of Arrival (TOA) of signals transmitted between the wireless handset and the network transmitters can be used. Positioning accuracies better than 50 m have been shown, given a proper geometry between the user’s mobile handset and the transmit towers (at least 3). The main advantage of such systems is that a special transmitter for positioning purposes is not required. The main disadvantage of telephone positioning systems is that the geometry of the base stations is optimized for communications, not positioning. As a result, the geometry may be very poor resulting in degraded accuracies on the order of 100-200 m. In cases where mobile phone can see only one tower to communicate it may not work at all.

3.10 Signal Strength

Another method of determining position involves the measurement of received signal strength. Such measurements can provide an approximate range between the user's device and the reference stations. A common approach is proximity detection – this approach uses a mobile receiver travelling through an area with a number of fixed transmitters at known locations which measures the power level received from each transmitter. The accuracy of this approach is correlated to the number and geometry of transmitters used and propagation paths between them. Examples of positioning systems based on received signal strength are some mobile phone positioning systems, RFID (Radio Frequency Identification) tag readers, or systems that use the known locations of Internet Wi-Fi hotspots to determine approximate location.

3.11 Two Way Ranging Systems

If you have several digital wireless radios capable of frequency hopping you need to synchronize clocks of such radios. This will require you to periodically measure two way distances between these radios. If you know absolute position of even one of these systems you can compute absolute position of all of them in a short while. Once these mobile radios learn their locations, any new system joining the network can easily find its own position as well (buy a series of two way ranging measurement to its neighbours). You can use this base structure to broadcast a pseudo-light type signal (now that you have a set of radios that know their location and also have a synchronized clock) for other users that do not possess two way communication, synchronized clock capabilities. Even though such systems can be expensive they can provide an alternative to GNSS in times of crises in areas of interest.

4.0 DEAD RECKONING SYSTEMS

Dead reckoning is a self-contained method of navigation that does not rely on any external infrastructure or external observations. Given a starting point system will measure the platforms movement, calculate resulting position change using time elapsed and add it to the previous position. While this provides a closed system basically impossible to confuse or deny its additive nature results in rapidly increasing unbounded errors.

After a short explanation of Inertial navigation, which is the most common dead reckoning system being used in almost all high value military systems, we will start exploring sensors used in dead reckoning system and not the way they are used, since methods are self-explanatory.

4.1 Inertial Navigation Systems

Among dead reckoning systems, Inertial Navigation Systems (INS) are the most complete and also the most complex. They consist of three linearly independent accelerometers and three linearly independent gyroscopes which measure all changes in body movement in 6 degrees of freedom space, continuously. Gyroscope measurements are used to calculate attitude changes of the platform while accelerometer measurements are used to calculate velocity and position changes of the platform in this orientation. Starting from a given initial position, the INS updates the path followed by the platform using these calculated changes which computes, not only the position but attitude and velocities as well.

Inertial Navigation Systems have several advantages. They are self-contained, in that no external infrastructure (such as a radio transmitter network) is required; they require no observations and databases; they provide continuous information; the output is available anywhere (under foliage cover, underwater, inside buildings); and they are unaffected by any outside interference, jamming and weather conditions. However, the accuracy of a standalone INS degrades with time (unbounded errors) due to sensor errors, calculation errors and it needs to be provided with its initial position. Accurate systems can be very expensive, large, heavy, and power hungry.

4.2 Inertial Sensor Technologies

The basic sensors within an Inertial Navigation System are accelerometers (to measure linear motions) and gyroscopes (to measure rotational motion). In inertial navigation systems due to the system additive characteristic, sensor errors dominate the accuracy and hence the usage area and price of the navigation system. In general gyroscope errors dominate error characteristics as they propagate by t^3 while accelerometer errors propagate by t^2. While low grade MEMS sensors can be a few dollars highest grade sensors price can be in million dollar range. Their sensitivity from lowest to highest may also differ million times or more.

4.3 Velocity and Distance Travelled Sensors

There are a number of sensors available to measure speed, velocity and distance travelled to varying degrees of accuracy. When coupled with other sensors such as heading determination systems, they can form a dead reckoning navigation system. When used as an aid to an inertial navigation system they provide error growth control.

Examples of such devices include odometers, pedometers, Doppler velocity sensors, airspeed sensors, water speed logs, visual odometry systems, zero-velocity updates, etc.

4.4 Speed Sensors

Land, air, and water speed sensors, although mechanically different, all provide similar information: the speed of the user relative to the surrounding environment. These sensors tend to be very reliable and inexpensive, however their measurement errors are environmentally dependent and must be calibrated for accurate applications.

In land vehicles, odometers, often called vehicle motion sensors (VMS), measure the number of wheel, engine or transmission rotations. The number of rotations multiplied by the wheel circumference provides the distance travelled, and the rotation rate provides the speed.

An air speed indicator uses a pitot tube to measure the difference between the static pressure and the total pressure. This difference is related to the speed of the air vehicle with respect to the air.

Water speeds can be measured with an Electromagnetic (EM) speed log. An EM log generates an electromagnetic flux that changes with the speed of water flowing over it providing the relative speed of the vehicle with respect to the water. Water speed can also be measured with a mechanical speed log: the flow of water over a propeller causes it to rotate.

4.5 Pedometers

A pedometer is a small device, usually containing a simple accelerometer, which counts the steps a user makes to determine distance travelled. Pedometers are inexpensive, lightweight, passive, self contained and readily available. However, because of variations in the length of a stride, errors are typically on the order of 10% of the distance travelled.

4.6 Doppler Velocity

A Doppler radar velocity sensor is a device that transmits and receives a low power radio signal, and deduces its velocity based on the shift in frequency of the returned signal as it reflects from nearby objects. This shift in frequency is known as the Doppler effect, and is directly related to the velocity (speed and direction) of the sensor.

Doppler radar systems are available commercially for automotive and traffic enforcement applications and are being adapted to unmanned navigation systems. These sensors provide very accurate user velocity; however, they are not covert, and the measured velocity is sensitive to user orientation.

4.7 Zero Velocity Update

Zero velocity updates (ZVU or ZUPT), or measurements of velocity=0, are most often used to control the error growth in inertial navigation systems (INS). A ZUPT can be made whenever a user, such as a land vehicle or a dismounted soldier, is known to be stationary. The concept is simple: when the INS is stationary, its known velocity (zero) can be used as a measurement to update the navigation processing filter. ZUPTs can be processed continually as long as the INS is stationary. They may be scheduled, requiring the operator to hold stationary for a short length of time. Additionally, periods of zero motion can be automatically detected by software and a ZUPT executed.

4.8 Visual Odometry

Visual odometry refers to the estimation of relative platform motion from visual data. The determination of motion parameters starts with establishing feature correspondences between consecutive image frames, either by feature tracking or feature matching. Motion parameters, such as velocity or distance travelled, can be accurately estimated through the application of geometrical constraints.

4.9 Magnetic Compass

Magnetic sensors determine heading by sensing the intensity and inclination of the Earth's magnetic field. However, local disturbances in the Earth's magnetic field caused by nearby permanent magnets, electric currents, or large iron bodies can dramatically affect the derived azimuth, or even prevent their use. The azimuth angles from magnetic compasses must be corrected for magnetic declination if they are to refer to true north. Magnetic declination, or the difference between magnetic north and true north, varies with position and time.

The sensors are passive, self-contained, of very small size, low cost, and lightweight. The accuracy of derived azimuths from magnetic compasses depends heavily on the degree to which the local magnetic field is being disturbed. When properly calibrated, heading accuracy can be on the order of 1 degree.

4.10 Gyrocompass

Gyrocompasses use gyroscopic technologies to determine the direction of the Earth's rotational axis, i.e., true north. Gyrocompasses measure the Earth's rotation rate (15 degrees/hour) in the horizontal plane. A measurement of zero indicates east while the maximum measurement (Earth's rotation rate times cosine(latitude)) indicates north.

They have two main advantages over magnetic compasses: they find true north, i.e., the direction of Earth's rotational axis (as opposed to magnetic north), and they are not susceptible to external magnetic fields. A typical ship gyrocompass can measure true north with better than 1 milliradian accuracy.

4.11 Barometric Altimeter

Inertial Navigation Systems are unstable in the vertical axis and if unaided will provide no useful height information. Dead reckoning by compass and distance travelled provides no height information at all. In difficult urban, subterranean environments, the knowledge of height is often critical to mission success.

Barometric altimeters provide a measure of altitude based on the measure of static atmospheric pressure. This pressure measurement is directly related to the height above mean sea level. Like many speed sensors, they tend to be very reliable and inexpensive. However, the pressure readings vary with weather conditions and must be corrected on a regular basis with a reference barometric altimeter at a known height and nearby location for long duration applications.

4.12 Radar Altimeter

For airborne applications, radar altimeters can be used to provide a very accurate measure of the height of the platform above the ground level. A low power radio signal is transmitted towards the ground, and the time required for the signal to reflect from the surface and return to the altimeter provides a direct measure of height above ground.

4.13 Water Depth

Used in underwater vehicles, depth sensors typically measure water pressure. A precision quartz crystal resonator whose frequency of oscillation varies with pressure-induced stress is thermally compensated to calculate depth and can achieve high accuracy over a broad range of temperatures. Accuracies on the order of 0.01% can be achieved.