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A Review of Position Tracking Methods

Timothy TJ Brooks[*1], Huub HC Bakker[1], Ken A Mercer[2] Wyatt H Page[3]
1Institute of Technology and Engineering, Massey University, Palmerston North, New Zealand
2Institute of Information Science and Technology, Massey University, Palmerston North, New Zealand
3 Institute of Technology and Engineering, Wellington, New Zealand
* Corresponding author ttjbrooks@gmail.com

Abstract

Accurate tracking of objects in the range of metres to hundreds of metres has widespread application and huge potential. This paper reviews methods of calculating the position of a remote object based on electromagnetic radiation from the radio to light frequencies. The methods discussed include: manual triangulation, time of flight, time difference of arrival and angle of arrival. For each method a description is given of the calculations and the equipment that is used and the advantages and disadvantages are stated. This paper also discusses the use of these methods for tracking multiple objects, and the suitability of using wireless electronic devices for positioning.

Keywords: Position, tracking, time of flight, time difference of arrival, angle of arrival, multiple objects, wireless, sensor, network.

1 Introduction

Methods of finding the position of a remote object with respect to a known location have been required for several hundred years. The first applications of these methods were road surveying, target ranging for artillery, and in map making.

Today the applications for accurate positioning are wide and varied. Examples include: personal navigation, smart weapon guidance, location of nodes in a distributed sensor network, tracing the origin of emergency calls made from mobile phones, and locating the positions of emergency locator beacons.

Due to this wide range of applications, many methods of position tracking have been proposed to suit the requirements of a particular task. This paper aims to summarise the literature regarding these methods, specifically the theory of operation, the equipment used, and the advantages and disadvantages of each method. The use of self-powered wireless electronic devices in these methods will also be analysed.

The methods discussed include: manual triangulation, time of flight, time difference of arrival and angle of arrival.

This paper will also describe the modifications required by each of these methods in a system designed to track the position of multiple objects.

2 Basic Triangulation

At the heart of many positioning methods is the idea of triangulation: the use of the properties of triangles to calculate distances. Credit for the discovery of the underlying theory of triangulation goes to the ancient Greek philosopher Thales[1]. Because of the ubiquitous nature of Thales' theorems in modern positioning methods, a basic description of triangulation is given here.

Given any two reference points it is possible to calculate the distance from one reference point to an object with knowledge of the angles between both references and the object and also the distance between the reference points. Figure 1 illustrates this.

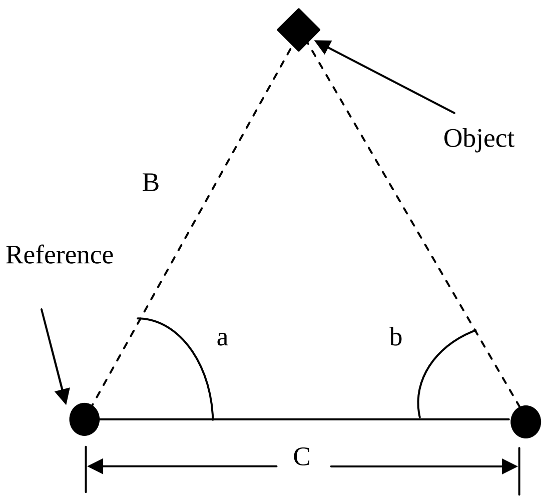

Figure 1: Mathematical approach to triangulation.

The distance *B* can be found by using the sine rule for triangles[2]. Equation (1) shows this formula rearranged to find this distance. Note that *a*, *b*, and *C* are all known.

$$B = \frac{C \sin b}{\sin(180 - a - b)} \qquad (1)$$

Originally triangulation was used for surveying and civil engineering purposes, and later for finding the range of targets for artillery strikes.

3 Modern Positioning Methods

3.1 Time of Flight (ToF)

This method uses the time taken for a signal to travel between the object and base station. By using the time, distance and velocity relationship the distance of the object from the base station can be found. With only one base station the position cannot be directly measured, only a distance from the reference point. The position of the source can be found in one of two ways: by measuring the angle deviation from a reference by using a system that is sensitive to direction, such as a directional antenna or a system in which the receiver must be pointing directly at the source for the signal to be received; or, use multiple base stations at different known locations (at least three are required to find the position). These methods are described in more detail below.

3.1.1 Distance Measurement

A ToF system that is used for calculating distance only can work in two ways. The signal could be sent from a node on the object to the base station and the time it takes for that signal to reach the station is used to work out the distance. The equation for this is shown below.

$$d = v.t \qquad (2)$$

Where d is the distance between the node and the base station, v is the velocity of the signal and t is the time taken for the signal to travel between the node and the base station.

This system has the severe disadvantage that the node and base station must be synchronized so that a timer starts exactly when the signal is sent to ensure that the calculation of time is accurate, if the signal is an electromagnetic wave then an error in time measurement of 1ns will result in an error in the distance measured of approximately 0.3m.

Because of this, most ToF systems send the signal from the base station and time how long it takes for the signal to travel to the object, be reflected, and return (called the round trip time). Assuming that the reflection time is negligible the ToF can be calculated by halving the round trip time. This system has the advantage that all of the timing is done at the base station and as such no remote synchronization is necessary. Also, with all of the transmitting and receiving equipment at the base station, the amount of equipment that must be placed on the object can be reduced considerably if not removed completely. This type of system is therefore feasible in situations where it is either inefficient or impossible to reach the object. Another advantage of this method is realized when using a laser as the signal carrier; because a laser can be made to be highly directional, interference from the environment is reduced.

Another carrier type that is used in positioning is ultrasonic waves. These are used in much the same way as lasers. Wolf[3] proposes a system for using ultrasonic waves to measure the position of an object in three dimensions.

Applications of this type of ranging include: surveying for road, bridge, tunnel and other civil engineering applications; range finding for use in adjusting rifle sites; airborne surveying[4]; range finding of objects to increase the functionality of both autonomous and teleoperated robots[5].

Some of the research currently in progress to increase the resolution of laser distance-measuring equipment include: magnification and measurement of the phase shift between two lasers[6] and a single photon counting method for use in depth profiling[7].

3.1.2 Multiple Base Station Position Measurement

In a ToF system that uses multiple base stations, the position of the object (which has a transmission node attached to it) is found by plotting the locus of points where the signal could have originated for each base station (BS). The position of the object is the point where all of the loci intersect. Figure 2 illustrates this method.

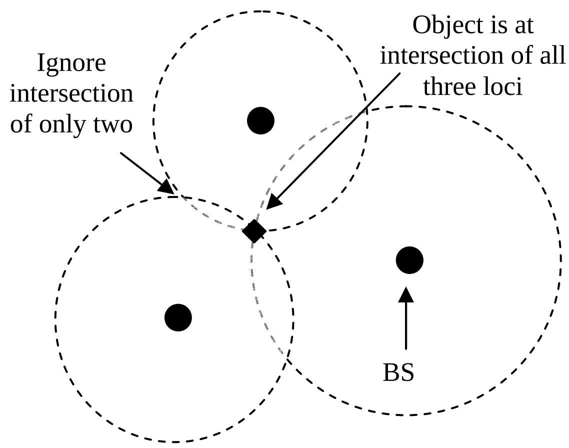

Figure 2: ToF positioning method.

This type of system is best used with an omni-directional signal carrier, such as radio waves. This allows the object to be anywhere within range of all of the base stations. Also, the object can be moving if there is the ability to make multiple measurements with the system.

One of the disadvantages of this system is that for it to have such a wide area of effect the nodes and base stations must be omni-directional. The system may be vulnerable to interference from outside sources or, more importantly, multi-path fading caused by part of the signal bouncing off another object in the local area. The figure below shows how multi-path fading occurs.

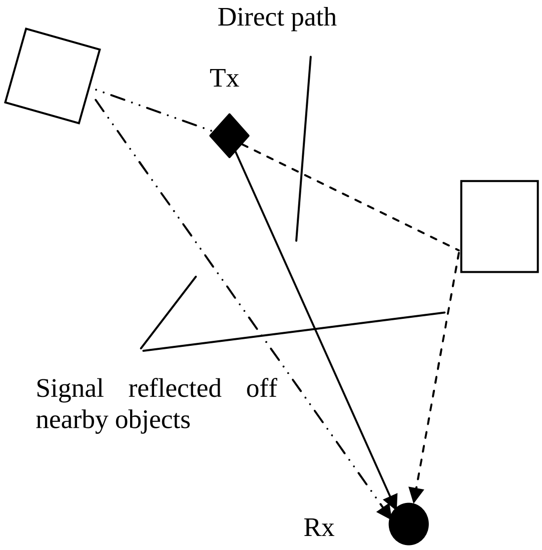

Figure 3: Base station experiencing multi-path fading.

Note that the reflected paths are longer than the direct path.

There are several methods currently being researched to combat the problem of multi-path fading. One is to shape the transmitted pulse so that the available bandwidth is used more completely[8]. Another similar method is to use Ultra Wide Band (UWB) transmissions[9].

Another disadvantage of the multiple base station system is that it requires that the stations each be synchronized with the node.

In general, time of flight has a large disadvantage when used in a system where a signal is transmitted from the object in response to a signal from the base stations. The electronics on the object must receive and recognise the querying signal then organize and send the response. In such a situation the reflection time of the signal will not be zero and must be taken into account or the ToF calculations will have an offset error.

3.2 Time Difference of Arrival (TDoA)

In this system a base station measures the difference in time of the arrival of two or more signals. Using this data and the time, distance and velocity relationship, the base station can calculate its position relative to the signal sources. For this method to work the locations of the signal sources must be known.

As an example, GPS uses this method[10]. Timing is kept accurate in GPS through the use of synchronised atomic clocks on board each satellite.

In GPS there are multiple sources sending data to a single receiver. A system in which a single node sends a signal that is received by multiple base stations would an alternative application of this method. This type of system would work in the same way as the GPS system. The range of this system is the area in which the signal from the node can be received by at least three base stations. This range could be expected to be of the order of metres to hundreds of metres depending on the terrain and equipment being used. An example of a local area system that works in this way is proposed by Cheng[11].

The major advantage of this method is that it does not require the node and the base station to be synchronized with each other since the time measurements at the base station begins when the first signal arrives. However, this method does require that the time measurement system be accurate. Inaccurate measurements of the time difference will result in erroneous calculations of distance and inaccurate measurements of position. In the GPS system this problem is overcome by measuring the TDoA of the signal from a fourth satellite. This extra information allows the GPS receiver to fine tune its local time. The principle of using redundant information to increase accuracy can be applied to any TDoA system.

One of the major disadvantages of the GPS system itself is that corrections must be made for issues arising from relativity. The first issue is that the GPS satellites are moving with a high velocity relative to a base station, this causes the satellites' onboard clock on the to run approximately 7 microseconds slower per day compared to a ground clock. The second issue is the satellites experience less gravity, which causes their clocks to run approximately 45 microseconds faster each day compared to a ground clock. Therefore the total correction that must be applied to the clocks in the satellites is –38 microseconds over the course of each day [12].

An alternative to using the GPS signal for timing is to have an atomic clock used in the base station. Atomic clocks are currently in development that will fit in an integrated circuit and have similar accuracy to GPS clocks [13]

For systems that do not have the advantage of highly accurate atomic clocks, other methods of increasing the accuracy of timing are required. One of the major sources of inaccurate timing comes from jitter in the oscillator of a system. Jitter is small variations in the frequency of the output signal of an oscillator. This variation can come from a range of sources including: substrate and power supply noise, which causes switching components to change state at the wrong time[14], interference from environmental sources, (including changes in temperature, which has an effect on the propagation delay of circuits), analogue signal jitter[15], vibration of the crystal from external sources, and variations in crystal oscillator manufacturing[16].

Current research is underway on increasing the accuracy of these oscillators, such as by Zamek[17] who proposes a new method of estimating jitter, or Lisoweic[18] who describes a frequency reference source that is controlled by the GPS time signal.

Examples of TDoA systems include: a small transmitter node placed inside a soccer ball to allow calculation of the ball's position accurate to within a centimetre[19], mobile position location standards for 3G mobile phones[20] and the location of origin of emergency calls made from mobile phones[21].

For background reading in these applications see Stensgaard[22], Wylie-Green[23, 24] and Laitinen[25].

TDoF is suitable for use in wireless sensor networks that are either static or mobile. All that is required is that at least three base stations of known position that are within range of all of the other nodes.

3.3 Angle of Arrival (AoA)

This method involves using a receiver that can calculate the angle of incidence of an incoming signal with respect to a reference. An example of such a receiver might be a directional antenna that can calculate what direction an RF signal originated from.

One example of a directional antenna is the phased array antenna in which the incident angle of the incoming signal can be calculated by measuring the phase difference of the incoming signal at several receiving elements aligned in a known pattern. Another example is the Doppler antenna in which the Doppler shift of an incoming signal is measured with respect to an antenna array that simulates a single antenna moving in a circle[26].

The AoA method can be used to calculate position in one of two ways. In the first, the angle of arrival information is combined with data from the time of flight distance method (see section 3.1.1) to get the position of an object in polar coordinates. This method has the distinct advantage that it requires only one base station.

In the second method, two or more AoA stations are set up at known distances from each other, the AoA of an incoming signal is calculated at each station and the theories and equations of triangulation are used to calculate the position of the source (see section 2).

The main advantage of using a purely angle based system is that there is less need for accurate timing in the system. Therefore the oscillator jitter, gate propagation delay and other factors that affect timing, have less of an effect on the position uncertainty.

Another advantage is that by increasing the number of sensing stations, the redundant data can be used to reduce the position uncertainty. It should also be possible to have the positions of the extra sensing stations calculated by using the AoA method from the stations of known position.

The major disadvantage of this method is that the sensing stations must have a fixed reference for the calculated angles to have any meaning. The implication of this disadvantage is that the AoA antennas must be static unless some way of measuring the orientation of the station with respect to a reference is included in the base station system.

The major factor that affects the accuracy of an AoA positioning system is the angular resolution of the antennas used. As the minimum angle that can be resolved increases so to will the error associated with each measurement. Furthermore, for a given angular resolution the boundaries of the error of positioning will increase when the object is further away from the antenna. By minimizing the angular resolution and also the range of an object to the nearest base stations the positioning error can be minimized.

4 Tracking multiple objects

Many present day applications of position calculations require that the positions of many objects be tracked. Examples of the applications of multiple object position tracking include: finding positions of sensors in a distributed wireless sensor network, tracking animal movements and biometric data[27], increasing the independence of the elderly or infirm by tracking their behaviour in their home[28], and for businesses to track their product shipments, assets or employees[9].

All of the systems that have been described could be used to track the positions of multiple objects, but they would require some modification to that described.

The most important modification is that each object to be tracked must have some uniquely identifiable characteristic so that when the calculations are being made the base stations are not confused by multiple signals that appear the same. The following sub-sections describe methods of tracking multiple objects. Note that all of these methods are able to calculate the positions of multiple objects, however, the requirements of a particular situation may make any of these methods unfeasible.

4.1 Laser/Ultrasonic Based Tracking

In a laser or ultrasonic based system individually identifying each object is relatively easy because the transmitter is directed towards the object whose position is required. Problems arise when the objects are moving (the system must predict the movement to keep that object aligned with beam). When there are multiple objects that converge and diverge the system can no longer distinguish which is which.

4.2 Unique ID Solution

This solution involves having some form of identification on each of the objects, such as a radio frequency identification (RFID) tag or a Dallas 1-wire ID tag[29]. These transmit a unique bit stream when prompted by an electronic interrogation device (called a reader). This method is appealing because it is very easy to include an ID into most types of wireless sensor nodes.

This ID signature could be used in conjunction with any of the methods presented here to calculate the positions of each object in turn.

One limitation is that the system could only handle a finite number of objects. The exact number of objects is defined by the available processor capacity and the maximum interval between successive position measurements of a particular object set by the requirements of the system.

Another major disadvantage is that there may be an uncertain delay in the query signal being received and the reply transmission being sent (the reflection time). As has been stated, this delay will affect time-based calculations of distance. It is easy to take account of this delay if it is a constant (by subtracting the reflection time before halving the round trip time), however this delay will be affected by all sources of jitter and propagation delay (see section 3.2). Accurate models of the relationship of this jitter and propagation delay would help this type of system to correct for this uncertain reflection time. It should also be noted that this disadvantage would not affect a pure angle of arrival system since this method is not as dependent on time.

Another method of using the ID information is to have each of the nodes transmit on a pseudo-random basis. This would remove the need for the nodes to be interrogated by one of the base stations, thereby reducing the complexity of the nodes. The drawback of this method is that without control over when a particular node transmits its ID there is a possibility of collisions. That is two or more transmissions occurring at the same time, making all of the signals unreadable because of interference. Pseudo-random transmission is very similar to an early network protocol for computers called the Aloha protocol. Like Aloha, the performance of the system will degrade exponentially as the number of nodes in the system is increased. Anti-collision algorithms are common in multiple access RFID systems[30].

4.3 Self Positioning

In this method each of the nodes calculate their positions based on signals received from known references and one of the methods described above. Note that this is the configuration that GPS uses.

Because the signals in this system are all broadcast to all of the nodes there is the advantage that this scheme will allow an unlimited number of nodes to track their own positions so long as they are within range of enough of the reference signals (in most cases three are required for two dimensional positioning). The disadvantage is that each object that is to be tracked must have a node and that node must be interrogated for the position data to be used by an outside agent.

5 Conclusions

Several methods for position tracking of objects have been described and discussed. It is clear that most of them are viable for position tracking in the metre to hundreds or metres range; many trading off accuracy, complexity and cost. The systems have also been shown to be suitable for use in most wireless sensor networks that are distributed over this range. While RFID tags will soon be available at costs to be measured in cents, wireless sensor networks also hold significant advantages, as they are able to send more than just an ID signal. This would useful in any system where extra information is desirable.

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