TRAIN POSITION DETECTION

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SUMMARY

This paper describes a method of improving the determination of train positions that is particularly applicable in areas where track circuits are not available. The method uses multiple GPS antennas for position and heading determination.

One of the key problems with standard GPS solutions is the difficulty in resolving the track that the train has taken at a junction. Parallel tracks may lie within the resolution ambiguity of standard GPS and DGPS position measurements. We propose that attitude determination be used to determine the path that the train has taken at a track junction. The document then explains the equipment and methods that were considered best for solving these problems.

INTRODUCTION

At any location where a train can change tracks, the heading of the train must change if it is to move from its current track. This suggests that with knowledge of the track geometry and train heading, we can unambiguously determine the position of the train.

Attitude determination using the Global Positioning System (GPS) is based on carrier phase measurements. If multiple antennas are employed, the relative carrier phase can be determined. A signal travelling at the speed of light arrives at the antenna closer to the satellite slightly before reaching the other antennas.

The relative range between GPS antennas mounted on a locomotive can be determined by measuring the difference in carrier phase between antennas. (Four GPS satellites must be tracked in order to solve for the three components of Cartesian relative position and receiver clock bias.) When multiple antennas connect to the same receiver, each signal path shares a common time reference, the measurements are independent of the receiver clock bias, and the mechanical placement of the antennas is known. Only three GPS satellites are then required to solve for the attitude.

Using GPS in this kind of application has a great advantage over many other types of heading sensors. A GPS heading sensor has no moving parts, and hence a high resistance to shock and vibration. Stable measurements can be obtained due to the large mechanical and thermal inertia of the GPS system. An additional advantage of the GPS system (over systems that involve magnetic compasses) is its reference to “true” geographic north. GPS measurements have fast initialisation times, and are free of problems such as drift.

ANTENNA CONFIGURATION

The configuration chosen for the antennas can have an impact on the performance of a multi-antenna system. The ideal configuration should minimise the errors as much as possible. In practical situations, compromise is often necessary due to physical constraints.

The accuracy of the attitude measurements is inversely proportional to the distance from one antenna to the next. This would imply that the best configuration would have the longest baseline between antennas. However, the complexity of integer ambiguity resolution is increased as the baseline length grows.

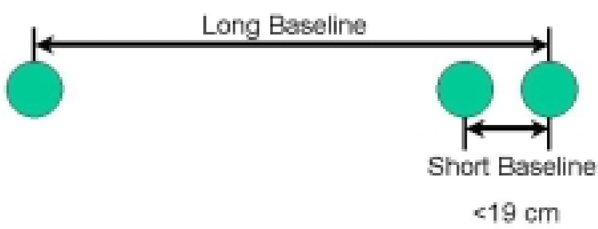

Figure 1 Antenna Configuration

An extra antenna can be used to improve attitude accuracy and reduce the complexity of the ambiguity resolution.

The optimal antenna configuration is one where the antenna baselines are equidistant and orthogonal. However this can be difficult to achieve when working with the restrictions involved with mounting on a vehicle.

An alternative solution is to place the three antennas in a straight line. Two of these antennas are placed with a baseline less than one carrier wavelength long, and the third is placed with a longer baseline along the same straight line. This collinear restriction and spacing will reduce the number possible solutions that need to be tested for attitude determination.

ATTITUDE DETERMINATION

Although there are dedicated attitude determination systems on the market today, these systems tend to be expensive. Dedicated attitude determination systems have been developed generally for aircraft applications, and provide attitude information in three dimensions. The attitude needs of an aircraft differ from the needs of a locomotive, as two-dimensional attitude is adequate for a rail bound vehicle. For this application it seems feasible to use a number of low cost sensors configured so as to optimise their usefulness in the railways.

There are several methods for increasing the reliability of low cost sensors. These methods include using a higher data rate, using a fixed angular constraint scheme and using Kalman filter estimation[1].

There have been investigations undertaken which examine the accuracy of low cost and high cost GPS receivers when used for attitude determination[2, 3, 4 and 5]. The overall conclusion from these studies is that the accuracy of high cost and low cost systems for attitude determination is comparable.

The general process for attitude determination using multiple GPS receivers is as follows:

1. GPS measurements are taken (including Ephemeris Time, Pseudorange, Carrier phase and Doppler Measurements)
2. These measurements are then input to measurement equations (which consist of algorithms for processes such as double differencing and linearisation)
3. The output from the measurement equation used as an input for the integer ambiguity resolution.
4. The integer ambiguities are then input to the measurement equation.
5. The output from the measurement equation is then input into some form of relative positioning algorithm (such as least squares, Kalman filter and so forth)
6. The output from the filter is then transformed in terms of the coordinate system
7. The transformed output is then input to the attitude determination algorithm

The output from the attitude determination algorithm is the final output.

GPS OBSERVATIONS

GPS observations used to determine positions include pseudorange measurements, carrier phase measurements and instantaneous Doppler frequency. Carrier phase measurements are generally used in applications that require greater precision than provided by pseudorange measurements.

In attitude determination systems, the pseudoranges are used to determine the platform position at each instantaneous point in time. The platform velocities are determined using the Doppler frequency measurements, and the attitude parameters are computed from the differential carrier phase measurements.

The pseudorange measurements can be summarised by the following equation[6]

$$P = \rho + c(dt-dT) + d\rho + d_{ion} + d_{trop} + \varepsilon(\rho_{mult}) + \varepsilon(\rho_{rx}) \tag{1}$$

where:
P = pseudorange measurement (m)
C = speed of light (m/s)
dt = satellite clock correction(s)
dT = receiver clock error(s)
$d\rho$ = orbital error (m)
d_{ion} = ionospheric correction
d_{trop} = tropospheric correction
$\varepsilon(\rho_{mult})$ = code multipath error
$\varepsilon(\rho_{rx})$ = receiver code measurement noise.

Carrier phase measurements can be used on short to very long baselines with high precision. The difference in phase between the transmitted carrier wave from the satellite and the receiver oscillator signal at a specified epoch is the phase observable. The initial and unknown integer ambiguity can be represented by a single bias term.

A cycle slip can occur when the tracking is interrupted due to blockage of the signals, weak signals or incorrect signal processing due to receiver software failure. Phase can generally be measured to 1% of the wavelength, for the civilian GPS frequency this translates to roughly 2 mm.

The carrier phase relationship can be written as

$$\Phi = \rho + c(dt-dT) + \lambda N + d\rho - d_{ion} + d_{trop} + \varepsilon(\Phi_{mult}) + \varepsilon(\Phi_{rx}) \tag{2}$$

where
Φ = $-\lambda\phi$ (Φ in metres)
N = integer carrier phase cycles ambiguity
λ = carrier wavelength (m)
$\varepsilon(\Phi_{mult})$ = carrier phase multipath error
$\varepsilon(\Phi_{rx})$ = receiver carrier phase measurement noise

As can be seen, there is an ambiguity in the number of integer carrier phase cycles, N. The resolution of this ambiguity is one of the main challenges in GPS attitude determination.

With two receivers placed closely together, we can virtually eliminate errors due to the satellite clock, the satellite orbit, and ionospheric and tropospheric effects. This can be achieved through differencing and double differencing. Double differencing gives the following result:

$$\nabla\Delta\Phi = \nabla\Delta\,\rho + \lambda\nabla\Delta N + \nabla\Delta\varepsilon_{multi} + \nabla\Delta\varepsilon_{rx} \qquad (3)$$

where:
∇ = differencing between satellites
Δ = differencing between receivers
$\nabla\Delta\Phi$ = double difference carrier phase measurement
$\nabla\Delta\rho$ = double difference range
$\nabla\Delta N$ = double difference ambiguity
λ = carrier wavelength (m)
$\nabla\Delta\varepsilon_{multi}$ = double difference carrier phase multipath error
$\nabla\Delta\varepsilon_{rx}$ = double difference carrier phase receiver noise

Remaining errors, in particular the internal receiver errors and multipath cannot be cancelled, and are amplified through the differencing procedure. Multipath can be reduced through signal processing techniques and the use of hardware such as multipath rejection choke rings. The type of receivers used also has an effect on the severity of multipath and internal receiver errors.

The Doppler frequency is the rate of change of the carrier phase. The major function of Doppler frequency measurements is estimation of velocities, however in kinematic applications it can be used for identifying and approximating cycle slips.

OTHER NAVIGATIONAL OPTIONS

There are many navigational options available on the market today. These include not only GPS and Differential GPS (DGPS), but also Doppler Radar, Inertial Navigation Systems, Proximity Beacons and Tag readers.

GPS receivers are a cost effective option. The errors for GPS do not increase with time, as many other systems do. If we can overcome the problem of GPS signal outages, this will clearly be the most feasible navigation option.

GLONASS is the Russian counterpart of GPS. If both these systems are integrated (GPS/GLONASS) then an improvement in the DOP is seen over either system used alone. When a GPS system is augmented by GLONASS there are improvements in overall satellite visibility and reliability. This method of GPS augmentation is cost effective when compared to augmentation via other means such as inertial navigation systems. The integration of these schemes is not straightforward. GPS and GLONASS use different reference frames for their time and coordinate systems, as well as different signal modulation techniques.

LOW SATELLITE VISIBILITY

We propose the use of the locomotive tachometer in addition to GPS where it is available. (While all locomotives are fitted with tachometers, it is only the more modern locomotives that have a readily accessible tachometer signal.)

If the GPS attitude determination calculations can be completed between GPS reports (typically one second), then it is not necessary to maintain a continuous lock on all of the satellites. A train could pass through a tunnel and regain attitude information shortly afterwards. Where there are no vital decisions to be made within or immediately after the tunnel (eg track junctions), this information is adequate.

However, there are situations where the satellites will not be in view and the complexity of the tracks will require attitude determination. Examples of this are switches or crossing loops that are within tunnels and deep cuttings, or in other areas of low satellite visibility. An example would be tracks that pass under shopping centre developments.

There are several options for maintaining GPS signals when the satellites are not visible. These include pseudo-satellites (pseudolites), synchrolites, and GPS repeaters. If the receivers can obtain GPS-like signals, they can still perform attitude determination. (The GPS repeater does not permit attitude determination).

1. Psuedolites

Pseudolites transmit a signal similar to the signal transmitted by GPS satellites. However pseudolites are located on the ground. This location means that they act differently from GPS satellites. Pseudolites represent an additional satellite that is always in view, ensuring continuous availability. Psuedolites should only be necessary when the train is travelling in an area with both low satellite visibility and high complexity.

2. Synchrolites

A synchrolite is similar to a pseudolite, however instead of synthesising a GPS-like signal as a regular pseudolite does, a synchrolite effectively reflects the signal from a satellite. The position on the ground from which the signal is rebroadcast is known, and hence the direct and reflected signals can be used to compute differential measurements of the satellite signals, hence eliminating the spatially correlated errors that are present in the satellite signal. [7]

3. GPS Repeaters

Another possibility for ensuring coverage within tunnels and high multipath areas is the use of

GPS repeaters. An antenna can be installed at each end of the tunnel and the received signal rebroadcast within the tunnel. While this obviously only provides the train with the location of the external antenna, the GPS receiver retains its synchronisation. As soon as the train leaves the tunnel, the GPS receiver can produce accurate data.

GPS repeaters are low in cost (<$1,000) and can be easily installed. Many railway tunnels have radiating cable installations for mobile radio communications. A GPS repeater may be able to be connected to the existing radiating cable to provide extended distribution of the GPS signal at a very nominal cost. The losses along the cable will be high at the GPS frequency but at least a part of the tunnel will have adequate GPS signals.

4. Navigation Techniques

The table below summarises the information available and the techniques to be implemented under different conditions.

Track Position	**Procedure**	**Satellites Available**	**Info Available**	**Technique**
Initialisation	Tachometer	<3	Tachometer	None
Initialisation		≥3	GPS attitude potential	Integer Ambiguity Resolution
Just out of Tunnel	New satellites available	≥3		Integer Ambiguity Resolution
Travelling on well defined route	Map matching from GPS position and tachometer	<3	Tachometer	Use distance travelled in combination with map information to maintain estimate of position
Travelling on well defined route	Map matching from GPS position and tachometer	3	Tachometer and GPS attitude	Can use distance travelled and attitude information for estimate of position
Travelling on well defined route	Map matching from GPS position and tachometer	>3	Tachometer, GPS attitude and GPS position	Use GPS position in combination with track database to maintain rough position estimate
Train Stationary	Tachometer	<3	Tachometer	None
Train Stationary	Tachometer	≥3	Tachometer, GPS attitude, GPS position if >4 satellites	Integer ambiguity resolution validation performed, calibrate tachometer
Approaching point of interest	Tachometer, GPS position	≥3	Tachometer, GPS attitude, GPS position if >4 satellites	Integer ambiguity resolution validation performed, begin map matching at higher resolution
At point of interest	Tachometer, GPS position, GPS attitude	3	Tachometer, GPS attitude, GPS position if >4 satellites	Continue map matching with attitude information, verify position, set off appropriate alarms etc

Table 1 Summary of procedures under different conditions

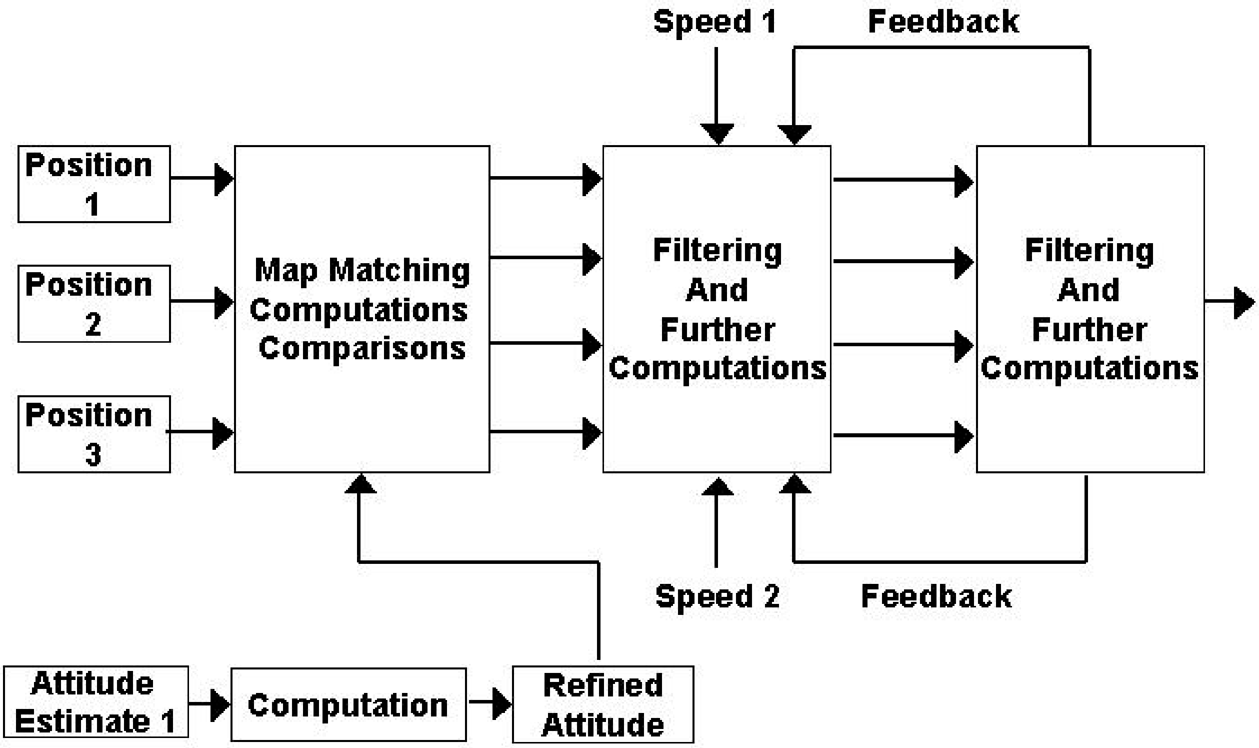

Figure 2 Block Diagram

REQUIRED RESOLUTION

Let us assume that the minimum centre-to-centre spacing of tracks is 4 metres, that there are 2.4 metres between the inner rails and approximately 1.45 metres between the two rails of the same track.

For a speed of 60 km/hr (16.7 m/s) assuming a maximum radius of curvature for a turnout as 679.3 metres, we obtain a rate of change of angle, $\Delta\phi/\Delta t$ = 0.0245 radian/s, or 1.406°/s. At slower speeds, this change of angle with time will decrease. Integrating these measurements over time will give the same overall change in heading, for this example ϕ = 2.648°.

At slower speeds, we will obtain more tangents to the circle. For example, if the train in the turnout is travelling at only 10 km/hr (2.8 m/s), and the angular displacement measurements are given at a rate of 1 Hz from the GPS attitude determination process, the train will take 11.3 seconds to traverse the first of the two arcs, and every second there will be a change in angle of $\Delta\phi$ = 0.234°.

Assuming that the uncertainty in position is a zero-mean Gaussian distribution we can calculate the maximum uncertainty and the required accuracy.

With a heading change of 2.648°, and a confidence level of 99.9999%, the required accuracy of the heading angle is 0.557°.

The table below shows the heading and pitch accuracy available for different baseline lengths. As can be seen here, for an inter-antenna distance (or baseline) of 0.9 metres we can obtain a heading accuracy of 0.27°. Should the baseline be extended beyond 0.9 metres, a greater level of accuracy would be achieved.

Inter-antenna Distance (m)	0.15	0.31	0.45	0.75	0.9
Heading Accuracy (°)	1.67	0.70	0.46	0.40	0.27
Pitch Accuracy (°)	3.27	1.66	1.07	0.89	0.43

Table 2 Angular Accuracy and Baseline length[8]

PROPOSED SYSTEM

A block diagram of the concept is shown in Figure 2. Using this system, we obtain several basic sets of measurements.

1. Position data for each antenna taken from the standard GPS messages
2. Attitude data derived from the GPS carrier phase measurements
3. Distance information from the tachometer
4. Velocity information from the GPS measurements and speed information from the tachometer information differentiated with respect to time
5. Angular rate of change

Some of this information is only available when there are a certain number of GPS satellites visible, and others are calculated through differentiation. The tachometer information is assumed to be available at all times.

We can use all this information together to provide a robust position determination system. The position, distance and attitude data is processed and filtered then compared with a map database.

Since the train location is constrained by the track, aberrations in the position calculation may be discarded. The heading (attitude) information can be used to determine when the train has diverged from its previous track, thereby increasing the effective resolution of the train position.

A similar arrangement has been proposed in a recent IRSE technical paper[9]. The technique described in that paper is based on Differential GPS receivers, which require continuous transmission of GPS difference data to the train. Our proposal obviates the need for differential data, using attitude determination to improve the accuracy and resolution of the standard GPS data.

CONCLUSION

There is ample evidence of the consequences of inaccurate position information for trains. The lack of position information can lead to accidents and inefficient operation.

Since the abolishment of Selective Availability the use of GPS seems an increasingly obvious solution to many of these problems. The solution proposed here has sufficient accuracy to overcome these problems in a simple and cheap manner.

It has been found in this study that the use of GPS carrier phase measurements, with the appropriate software algorithms, can provide accurate real time information about train location.

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