Geoinformatics 2004
Proc. 12th Int. Conf. on Geoinformatics – Geospatial Information Research: Bridging the Pacific and Atlantic
University of Gävle, Sweden, 7-9 June 2004

A TEST-BED SIMULATOR FOR GPS AND GIS INTEGRATED NAVIGATION AND POSITIONING RESEARCH: - BUS POSITIONING, USING GPS OBSERVATIONS, ODOMETER READINGS AND MAP MATCHING

Jing Li[1], George Taylor[2], Chris Brunsdon[3], Andrew Olden[4], Dörte Steup[5] and Marylin Winter[6]
GIS Research Centre, School of Computing, University of Glamorgan, CF37 1DL, Wales
[1]jli@glam.ac.uk, [2]getaylor@glam.ac.uk, [3]cbrunsdo@glam.ac.uk, [4]aolden@glam.ac.uk, [5]dsteup@glam.ac.uk,
[6]mwinter@glam.ac.uk

Abstract

A test-bed application, called Map Matched GPS (MMGPS) processes raw GPS output data, from RINEX files, or GPS derived coordinates. This developed method uses absolute GPS positioning, map matched, to locate the vehicle on a road centre-line, when GPS is known to be sufficiently accurate. MMGPS software has now been adapted to incorporate positioning based on odometer derived distances (OMMGPS), when GPS positions are not available. Relative GPS positions are used to calibrate the odometer observations. In OMMGPS, GPS pseudorange observations are combined with DTM height information and odometer positions to provide a vehicle position at one second epochs. Generally, odometer positioning is used much more often, to position the vehicle, than GPS. Typically the ratio is 7:3 odometer positions to GPS positions. In total, over 15,000 vehicle positions were computed using OMMGPS.

The described experiment used GPS observations taken on a bus on a predefined route, hence the correct road is always known. Therefore, map matching techniques are used to improve the GPS positioning accuracy, and to identify grossly inaccurate GPS positions. Calibrated odometer corrections are made using odometer count at the current epoch and relative GPS distance travelled. If a GPS position is detected to be inaccurate, it is not used for positioning the bus, or for calibrating the odometer correction factor.

In general the position quality provided by GPS alone was extremely poor, due to multipath effects caused by the urban canyons of central London. In the case of one particular trip, OMMGPS provides a mean error of position of 8.8 metres compared with 53.7 metres for raw GPS alone.

INTRODUCTION

Global navigation satellite systems (GNSS), such as the Global Positioning System (GPS) have been increasingly used in real time tracking of vehicles. Especially, when GPS is integrated with ever powerful geographic information system (GIS) technologies, the accuracy and reliability of low cost standalone GPS receivers can be significantly improved to meet the technical requirements of various transportation applications of GPS such as vehicle navigation, fleet management, route tracking, vehicle arrival/schedule information systems (bus/train) and on demand travel information.

There have been many attempts to improve the reliability of vehicle positioning through the fusion of observations obtained by the integration of various positioning and navigation instruments. The vast majority of such systems use a Global Navigation Satellite System (GNSS), for absolute positioning, and a variety of other sensors to provide relative positioning. The usual model being to use Global Positioning System (GPS) to position a vehicle whenever possible, and use some form of inertial navigation system (INS), or dead reckoning (DR) system; odometer, gyro, compass, to determine a vehicle's position relative to an initial position.

Kealy et al. (1999) and Ramjattan (now Kealy) and Cross (1995) describe a typical solution, integrating GNSS and DR using a Kalman Filtering technique. In this experiment a test route for the system was established in the centre of Perth, Western Australia. The results of this work found that "… DGPS/DR solution starts to degrade from 1m to errors as much as 35m by the end of a 10 minute period." (Kealy et al., 1999). Kalman filtering techniques do have an inherent problem, for vehicle navigation, on road networks, "in terms of stability, computational load, immunity from noise effects and observability" (Chiang et al., 2002). The performance of the filter is heavily dependent on the models used. The model used is a compromise between a statistical predictive dynamic model and the measurement (observation) model. If too much weight is given to the dynamic model, an overly smooth track is the result, i.e. rapid changes of direction are not recognised quickly enough. If too much weight is given to the measurement model, errors would be construed as sharp changes in direction. Devising the correct model is very difficult, and without a very good model a Kalman filter will deliver the wrong result. Other accounts of using a Kalman filter for multi-sensor vehicle navigation are given by Stephen and Lachapelle (2000), using GPS and low cost gyro, Petrovello et al. (2003) provides an informative discussion on levels of integration, also see Mezentsev et al. (2002). Hailes (1999) use Kalman filtering with map-matching.

Fei et al. (2000) describe fuzzy logic techniques as an alternative to Kalman filtering for GPS/INS integration. Furthermore, Mayhew and Kachroo (1998) compare solutions using various configurations of GPS, steering position, odometer, gyroscope, forward accelerometer and map-matching, with sensor fusion methods Kalman filtering, rule based and fuzzy logic. Chiang et al. (2002) have developed a GPS/INS multi-sensor navigation system that utilises an artificial neural network (ANN) as another alternative to Kalman filtering.

Over the past four years a group of researchers from the GIS Research Centre, School of Computing, University of Glamorgan, have designed, development and implemented a software application package for researching algorithms and techniques to improve GPS based map matching for navigation and tracking. This test-bed application, called Map Matched GPS (MMGPS) processes raw GPS output data, from RINEX files, or GPS derived coordinates. It provides linkage to a GIS for access and analysis of appropriate spatial and related attribute data (primarily road and height information). MMGPS identifies the correct road on which a vehicle is travelling on, and snaps the vehicle position onto that road. Furthermore, MMGPS corrects the derived position using its own computed correction parameters; Correction Dilution of Precision (CDOP), using history of previous position estimates and road geometry (Blewitt and Taylor, 2002). Various research experiments utilising MMGPS have been conducted and results have been fully described in Taylor et al. (2001).

Since the main objectives of this work are to determine both the accuracy and reliability of position, of a public transport bus, that can be provided using Global Positioning System (GPS), odometer and map matching techniques, a new algorithm has been developed that integrates odometer observations with existing Global Positioning System (GPS) map-matching software, called MMGPS. Now called OMMGPS with odometer observations. In OMMGPS, height information obtained from digital terrain models (DTM) are used to obtain 3D GPS point positions, when only three GPS satellites are visible to the receiver. More importantly, height aiding improves the accuracy of GPS point positions with poor satellite geometry (high PDOP), and when severe signal multipathing occurs (multiple reflected GPS satellite signals).

The developed method uses absolute GPS positioning, map matched, to locate the vehicle on a road centre-line, when GPS is known to be sufficiently accurate. When this is not the case, odometer readings are used to locate the vehicle on a road centre-line. Relative GPS positions are used to calibrate the odometer observations. The accuracy of this method is a function of the frequency of accurate GPS points, reliable map-matching and correct odometer calibration. Standard Ordnance Survey (OS) digital plan and height map products were used for road map matching and height aiding. A number of trips along a bus route were made to test the method. A typical result of map matched GPS positioning is shown in Figure 1.

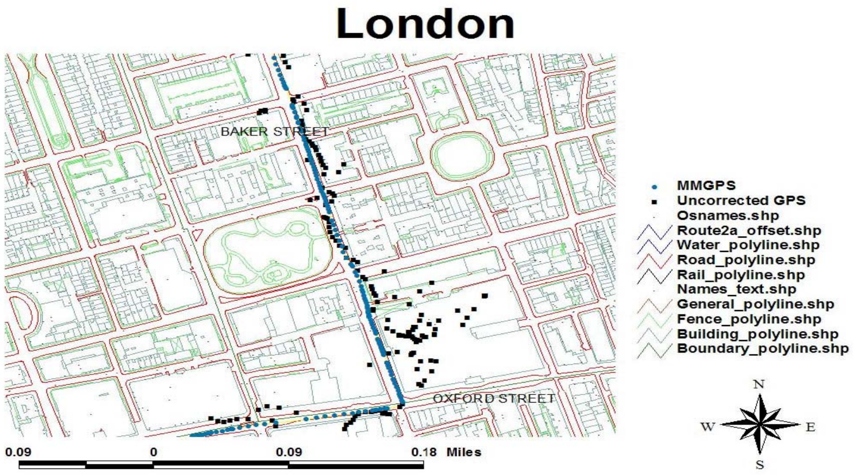

Figure 1: Map Matched GPS positions (MMGPS).

METHODOLOGY

The general approach that was taken, was to use GPS to position the vehicle, and also to calibrate the odometer readings, but only when GPS was available and of sufficient accuracy. At all other times odometer readings were used to position the bus. Odometer positioning was achieved by tracing the distance measured by the odometer along the bus route road centre-line, actually a 5m offset centre line was used, left of direction of travel, see Figure 1. Map matching techniques are used to improve the GPS positioning accuracy, and to identify grossly inaccurate GPS positions. The previous 10 GPS/odometer positions are used for map matching calculations.

Map matching

The existing MMGPS software has been adapted to incorporate positioning based on odometer derived distances, when GPS positions are not available. The main map matching criteria for a snapping a **Raw** GPS position to a road centre-line **Ref** GPS position, are that each of the following is below a set maximum value:

Distance error (absolute value of the difference between **Raw** distance and **Ref** distance, between the current and previous epochs).
Bearing error (absolute value of the difference between **Raw** bearing and **Ref** bearing, between the current and previous epochs).
Residuals of CDOP
Maximum distance of **Raw** GPS position from the road centre-line

Also, that the number of satellites visible to the receiver is the same for current and previous epochs.

If a GPS **Ref** position passes the check, it is used for positioning the bus, and for calibrating the odometer correction factor. Otherwise the position of the bus is derived from the calibrated odometer distance, and the odometer calibration correction factor is not updated. The values used for map matching, are obviously open to adjustment, or tuning, for different road geometries and for different environmental scenarios.

Distance correction factor

The previous section assumes that distances obtained from odometer readings are multiplied by a *correction factor* C, so that the distance supplied to OMMGPS is actually Cd rather than just d. It is not reasonable to assume C is fixed, as different roads, and indeed different road conditions on the same road will all influence C. For this reason, when GPS signals and odometer signals are both available, we will calibrate C over a time window by comparing distances travelled based on odometer readings with those estimated from the GPS (i.e. relative distances between two GPS points). If the GPS goes offline, the value of C obtained just before the GPS signal is lost (or regarded as unreliable) is used together with the odometer method to estimate location (i.e. calculate the current odometer position based on the previous GPS or odometer position and the current odometer reading which is multiplied by a correction factor C).

Estimating C

C can be regarded as a correction factor between odometer-based distance estimates as used above, and those obtained from the GPS-based method. At each second t, we obtain an odometer distance, d_t, and GPS-based coordinate estimates[1] (X_t, Y_t, Z_t). Here we assume d_t is a cumulative variable, so that the distance travelled between t–1 and t is $d_t - d_{t-1}$. Call this Δd. Also, from the GPS measurements, we can compute the cumulative distance travelled using OMMGPS. Call these distances D_t. Similar to the odometer distances, define ΔD as $D_t - D_{t-1}$. Thus, a model of the relationship between Δd and ΔD is

$$\Delta D_i = C\Delta d_i + error$$

We can calibrate this model by estimating C using least squares techniques - that is, choose C to minimise the expression

$$\sum_i (\Delta D_i - C\Delta d_i)^2$$

It may be verified that in this case, the estimate for C is

$$C = \frac{\sum_i \Delta D_i \Delta d_i}{\sum_i \Delta d_i^{\,2}} \tag{1}$$

However, this assumes that C is a constant correction factor. In reality, C is likely to change, depending on traffic conditions, road shape, weather and so on. A more realistic model allows C to vary with time, so that at each time t we have a distinct C_t. One approach in this situation is to estimate C according to the same model, but to use a `moving window' least squares estimate. At each time t we consider only the values for ΔD_i and Δd_i in a time window of k seconds - so only data from times t–k,t–k+1,..., t is considered. At time t+1 the data from time t–k is dropped, and that for time t+1 is added. Also, a weighting scheme is used in the least squares method, so that the squared errors for data close to t have a higher weighting. This gives an estimation method which places more emphasis on minimising errors close to time t. In this case, the least squares expression to be minimised is

$$\sum_{i=0\ldots k} w_i \left(\Delta D_{t-i} - C_t \Delta d_{t-i}\right)^2$$

where w_i is the weight placed on the error at lag i seconds before time t. In this case, we have

$$C_t = \frac{\sum_{i=0\ldots k} w_i \Delta D_{t-i} \Delta d_{t-i}}{\sum_{i=0\ldots k} w_i \Delta d_{t-i}^{\,2}} \tag{2}$$

Weighting scheme for w_i

Some thought should be given to the weighting scheme for the w_i's. Obviously, we wish for a time-decay effect, so that $w_0 > w_1 > \ldots > w_k$. One possibility is to choose an exponential fall-off up to w_k, so we could choose $w_k = \gamma^k$, provided $\gamma < 1$. Note that we may fix $w_0 = 1$ without loss of generality. We may experiment with different values of k and γ in order to obtain the best performance of the tracking algorithm as a whole. Thus, the estimate for C_t may be written as

$$C_t = \frac{\sum_{i=0\ldots k} \gamma^i \Delta D_{t-i} \Delta d_{t-i}}{\sum_{i=0\ldots k} \gamma^i \Delta d_{t-i}^{\,2}} \tag{3}$$

Height aiding

In OMMGPS height aiding is used throughout to add an extra equation in the least squares approximation computation of GPS position. Height information obtained, using bilinear interpolation, from a digital terrain model (DTM) are used to obtain 3D GPS point positions, when only three GPS satellites are visible to the receiver.

More importantly, height aiding improves the accuracy of GPS point positions with poor satellite geometry (high PDOD), and when severe signal multipathing occurs (multiple reflected GPS satellite signals). The number of GPS positions computed is nearly always increased by using additional height information, displayed in Table 1. Trip 3.4 is the exception.

Table 1: Number of GPS positions computed.

Trip no.	GPS only	GPS +Height Aiding
3.4	3834	3834
4	3468	3635
6	3320	3991
9.2	3713	4014

IMPLEMENTATION

OMMGPS consists of a Dynamic Link Library (DLL), written in C++, together with a GUI for use in ESRI's GIS products ArcView or ArcGIS. The GUI was originally written in ArcView's Avenue and has recently been translated to Visual Basic for use in ArcGIS (Steup and Taylor, 2003). The GIS is used to visualise the results graphically, using background OS mapping.

DATA PROCESSING AND RESULTS

A number of separate trips along the the bus route were made to test the method. During each of these trips, GPS and odometer observations were taken at each second, on the bus. Also, on each trip, the bus recorded the time when it detected a beacon at the beacon's known location, actually to a normal intersect with a 5 metre offset centre-line, see Figure 2. The positions of the bus at these times were used as the "true" position of the bus. There are altogether 13 beacons on route 2 which are used for determining OMMGPS accuracy.

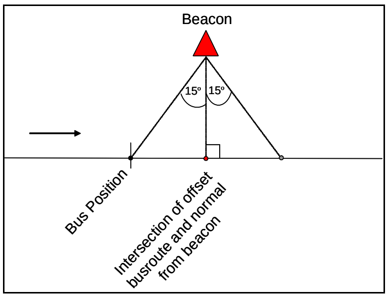

Figure 2: Beacon Detection.

Using this data the exact equivalent OMMGPS position used to calculate distances were obtained by interpolation, using the OMMGPS positions at the nearest second before and after the beacon detection time. This is simple linear interpolation.

A bus position was available at each second, either computed by GPS or by odometer observations. For the whole route, odometer positions are used much more than GPS positions: 70% Odometer positions, 30% GPS positions. For the calculation of OMMGPS position at beacon detection time for the 13 beacons used; 4 positions were calculated using only GPS and 9 positions calculated using only odometer. The results obtained for trip 4 are presented in Table 2. This bus trip is the one on which the algorithm was developed, and tuned, and shows the excellent potential of the method. The results of the other three trips, that were processed, i.e. trip3.4, 9.2 and 6 are shown in Table 3.

There is a substantial improvement in the accuracy of bus position using OMMGPS instead of only raw GPS; In the case of trip4, OMMGPS provides a mean error of 8.8 metres compared with 53.7 metres for raw GPS without odometer.

Table 2: OMMGPS statistics for all beacons- trip 4 and for 95% - trip 4.

	Error for 100%	Error for 95%
Mean	8.8m	5.2m
Standard Deviation	6.6m	3.6m
Range	18.7m	11.2m
Minimum	0.9m	0.9m
Maximum	19.6m	12.2m

Table 3: Average errors for all trips on route2.

Trip no	GPS only	OMMGPS	95% cut off OMMGPS
3.4	27.9m	11.3m	6.6m
4	53.7m	8.8m	5.2m
6	>100m	28.3m	14.1m
9.2	40.7m	22.8m	14.4m

CONCLUSIONS

A new algorithm that integrates odometer observations with the existing MMGPS map-matching software was developed and successfully implemented. This new algorithm is called OMMGPS. In OMMGPS, GPS pseudorange observations are combined with DTM height information and odometer positions to provide a vehicle position at one second epochs. Generally, odometer positioning is used much more often, to position the vehicle, than GPS. Typically the ratio is 7:3 odometer positions to GPS positions. This predominant use of odometer positioning is due either to GPS not being available, or GPS positions being considered to be too inaccurate to use. This lack of GPS positions is due to satellite masking by buildings (urban canyon effect) or the result of severe GPS signal multipath.

Four bus trips along the same bus route were used to test OMMGPS. The results obtained from these four trips are most encouraging. In total, over 15,000 vehicle positions were computed using OMMGPS. The positions provided by OMMGPS at the time of beacon detection can be considered to be a random sample of the accuracy provided by OMMGPS, compared to the accuracy provided by GPS alone. That is, if a GPS position was available at all, on or near the beacon detection time. The average error of OMMGPS positions, over all vehicle positions, using the random sample of beacon detection times, is 17.8m overall, and 10.1m for a 95% cut off. This compares with an average error for GPS alone of at least 55.6m overall.

Moreover, the effectiveness of OMMGPS is entirely dependent of the frequency and accuracy of GPS derived positions. The GPS data provided for testing compared very poorly with similar raw L1 pseudorange GPS data collected independently along the same bus routes, albeit with a much more expensive receiver and antenna. Similarly, receiver coordinates collected using another low cost L1 GPS receiver also provided improved positions, although this was most probably due to smoothing provided by this particular receiver’s own navigation filter.

In conclusion, the technique developed in OMMGPS works well, and can be further improved with more superior low cost GPS receiver technology or a more careful attention to its operational application.

ACKNOWLEDGEMENTS

This work was undertaken as part of a project commissioned by PA Consulting Group and Transport for London. Particular thanks must be given to Dr Phil White and Kenny Steele, for their help with the work, and problem solving and ideas.

REFERENCES

Blewitt, G. and Taylor, G., 2002: Mapping dilution of precision (MDOP) and map matched GPS, International Journal of Geographical Information Science, ISSN 1365-8816, 16(1), pp 55-67.

Chiang, K., Noureldin, A. and El-Shiemy, N., 2002: Multi-sensor integration using neuron computing for land-vehicle navigation. *GPS Solutions* 6(4), 209 – 218.

Fei, P., Qishan, Z. and Zhongkan, L,. 2000: The application of map matching method in GPS/INS integrated navigation system. *International Telemetering Conference, USA Instrument Society of America* 36(2), 728 – 736.

Hailes, T.A., 1999: Integrating technologies: DGPS Dead Reckoning and map matching. *International Archives of Photogrammetry and Remote Sensing* 32(2W1), 1.5.1 – 1.5.8.

Li, J., Taylor, G. and Kidner, D., 2003: Accuracy and reliability of map matched GPS coordinates: dependence on terrain model resolution and interpolation algorithm. *AGILE Conference on Geographic Information Science*, Lyon, France.

Kealy, N, Tsakiri, M. and Stewart, M., 1999: Land vehicle navigation in the urban canyon - ~A Kalman filter solution using integrated GPS, GLONASS and Dead Reckoning. *Proceedings of ION GPS 99 Conference*, pp. 509 – 518.

Mayhew, D. and Kachroo, P., 1998: Multi-rate sensor fusion for GPS using Kalman filtering, fuzzy methods and map-matching. *Proceedings of SPIE Conference on Sensing and Controls with Intelligent Transportation Systems*, Boston, Massachusetts, USA, November 1998, Vol. 3525, pp 440 – 449.

Mezentsev, O., Lu, Y, Lachapelle, G. and Klukas, R., 2002: Vehicle navigation in urban canyons using a high sensitivity GPS receiver augmented with a low cost rate gyro. *Proceedings of ION GPS 2000 Conference*, Portland, OR, USA, September 2002.

Petrovello, M.G., Cannon, M.E. and Lachapelle, G., 2003: Quantifying improvements from the integration of GPS and a tactile grade INS in high accuracy navigation systems. *Proceedings of ION NTM Conference*, Anaheim, CA, USA January 2003.

Ramjattan, A and Cross, P.A., 1995: A Kalman filter model for an integrated land vehicle navigation system. *Journal of Navigation, Cambridge University Press* 49(2), 293-302.

Stephen, J and Lachapelle, G., 2000: Development of a GNSS-based multi-sensor vehicle navigation system. *Proceedings of ION NTM Conference*, Anaheim, CA, USA January 2000.

Steup, D. and Taylor, G., 2003: Porting GIS applications between software environments. *Proceeding of the GIS Research UK 2003 11th Annual Conference*, London, pp. 166-171.

Taylor, G. and Blewitt, G., 1999: Virtual differential GPS & road reduction filtering by map matching. In: *Proceedings of ION'99, Twelfth International Technical Meeting of the Satellite Division of the Institute of Navigation*, Nashville, USA, pp. 1675-1684.

Taylor, G., and Blewitt, G., 2000: Road reduction filtering using GPS. *Proceedings of 3rd AGILE Conference on Geographic Information Science*, Helsinki, Finland, pp. 114-120.

Taylor, G., Blewitt, G., Steup, D., Corbett, S. and Car, A., 2001: Road reduction filtering for GPS-GIS navigation. *Transactions in GIS* 5(3), 193-207.