GPS-DR Integration Using Low Cost Sensors

B. R. Madhukar, R. A. Nayak, J. K. Ray, M. R. Shenoy

Accord Software & Systems Private Limited
Bangalore, India

BIOGRAPHY

B. R. Madhukar is a Senior Engineer at Accord Software and Systems. He has a B.E and M.E in Electronics and Communication from IISc, Bangalore. His area of interest is in receiver signal processing and GPS INS integration.

Rakesh A. Nayak was a Senior Engineer at Accord and is currently pursuing a M.Sc at the University of Calgary. He has a B.E. in Electronics and has been involved in GPS research since 1994 in the area of receiver hardware and software development and low cost sensor integration.

Jayanta Kumar Ray was a Senior Engineer at Accord and is currently pursuing Ph.D. at the University of Calgary. He has a B.E. and M.Tech in Electronics. He has been involved in GPS research since 1992.

M.R. Shenoy is the Program Manager for GPS related research and development at Accord. He has a B.E. in Electronics and Communications from the Bangalore University and M.E. in Integrated Circuits from the Indian Institute of Technology, Madras. He has been involved in GPS research since 1992.

ABSTRACT

A land navigation system integrating a low cost GPS receiver and Dead Reckoning (DR) sensors is developed. The DR sensors consist of an odometer and a vibrational gyroscope. A Kalman filter is developed, which uses all the available information and estimates an optimum solution for position, velocity and sensor errors. Position accuracy is tested under signal masking conditions. Field test data shows an average of 5.3% of distance traveled as cross-track error, under satellite blockage.

Investigations are carried out in a tight coupling mode of GPS-DR integration. In this mode, the DR estimated velocity aids the receiver-tracking loop, which is a second order Frequency Lock Loop (FLL). Simulation was conducted to observe improvements in acquisition and tracking due to velocity aiding. Later, experiments were performed using a GPS simulator and also using real data. Initial results show a 2dB improvement of acquisition performance and lowered the reacquisition search time by decreasing the search-frequency range. Tracking performance was also found to have improved by the DR aiding.

INTRODUCTION

GPS has made land navigation applications affordable and dependable. However there are many situations where GPS solution is either unavailable or unreliable. The former situation occurs when GPS signals do not reach the antenna due to shading effects resulting from high rise buildings and underpasses present in urban environment. The second situation arises from the bad geometry of the satellites in urban canyons. One of the important requirements in land navigation is the heading information and this is also unreliable when the vehicle has low dynamics. These situations demand improvements in the navigation solution provided by the GPS receiver. One of the methods to achieve this is to augment GPS with additional sensors like an odometer, rate gyroscope etc.

Kim et.al., (1996), Ren and Dedes (1995) and Weisenburger (1999) have used dead reckoning sensors to augment GPS for various applications. Krakiwsky et.al., (1988) discussed a Kalman filter strategy to integrate dead reckoning, map matching and GPS positioning. Ren and Dedes (1995) demonstrated the concept of integrating low cost sensors with non-linear smoothing of GPS measurements. Kim et al (1996) examined the integration of a piezoelectric gyroscope with GPS and subsequent gyroscope error compensation techniques. Weisenburger and Wilson (1999) used a Fibre Optic Gyroscope (FOG), speed signals from an ABS system and differentially corrected GPS to achieve reliable navigation in urban and typical highway conditions.

All these concepts use the complementary nature of GPS and DR systems. GPS has a very good long-term stability and poor short-term stability because of SA (Selective Availability) where as, DR systems comprising of odometer and gyroscope in general have relatively good short term stability and poor long term stability because of inherent drifts in the sensors.

The augmentation of GPS with in various configurations have been discussed earlier, one such method being the integration of GPS with IMU (Inertial Measurement Unit). Kriegsman et.al., (1977) demonstrated such a concept. However, the cost of such a system would be very high and not suitable for commercial land navigation applications.

Abbott (1995) discussed various errors in different sensors and their effect on the navigation solution. The sensors used are calibrated with aid from GPS and the quality of calibration will be limited by the accuracy of GPS. Removal of the SA by using DGPS corrections will improve the calibration of the DR sensors.

In this paper we discuss an implementation of integration involving a low cost GPS receiver (NAV 2000) with low cost DR sensors (odometer and Gyroscope). First, the choice of sensors is justified and then different architectures for data integration are described. Finally, the test set up and test results along with some simulation results are described.

LOW COST SENSORS

An objective of this integrated system was to keep the cost very low so as to make it viable for car navigation. Low cost sensors with suitable characteristics were chosen for integration. The sensors used for the experiment are an NAV-2000TM GPS receiver (Accord, 1998) developed by Accord, a piezoelectric gyroscope from Murata and a standard odometer. The receiver is a 12-channel single frequency L1 C/A code GPS receiver with standard features.

The gyroscope used as DR sensor is a piezoelectric vibrational gyroscope from Murata (ENV–05H), which measures the angular velocity of the vehicle. Such low cost vibrational gyros typically have bias and scale factor instability. They have significant temperature sensitivity and require constant calibration (Geier, 1998). The angular rate measured from the gyro has to be integrated over time to compute the vehicle heading.

A standard odometer using Hall effect principle was used for measuring the distance traveled. The cable adapter of the odometer was modified to fit for the test vehicle. The odometer is of low cost and is a standard accessory in most automobiles.

Other low cost options include accelerometers, magnetic compass etc. Accelerometers are not used as a little inaccurate calibration can cause an unaccounted small residual bias, which will result in significant error growth over time. Moreover, low cost gyros associated with the accelerometers will result in poor alignment and as a result gravitational acceleration can not be separated from the vehicle acceleration. A magnetic compass is not preferred, as the calibration of the compass is cumbersome and not a very practical option for automobile applications. On the contrary, an odometer is quite reliable and once calibrated, the parameters do not change drastically under normal operating conditions. Unlike a magnetic compass, an external electric or magnetic field will not influence a gyroscope.

INTEGRATION ARCHITECTURES

The possible architectures for GPS-DR integration are:

1) *Uncoupled mode*: This combines the GPS and DR data such that the integrated solution does not affect either of the sensors and there is no feedback to either of them. This is suitable for high accuracy secondary sensors.

2) *Loosely coupled mode*: Here the GPS is the primary sensor that calibrates the DR sensors. The accuracy of the system is determined by the accuracy of the GPS alone. The data can be integrated at two levels:

   a) Navigation Solution Level: The navigation solution, mainly position and velocity, are used to calibrate the odometer and gyroscope. This is discussed further in the paper.

   b) Measurement Level: Here the data integration is done at pseudorange and deltarange level. This is much more accurate than the previous case but is more complex. Kim et al (1996) have discussed similar integration techniques, where positioning using two satellites and DR measurements is explored.

3) *Tightly coupled mode:* The data from the integrated navigation solution is used to GPS tracking loops, thereby reducing the bandwidth of the carrier tracking loops in the GPS sensor module. This reduces the dynamic stress on the Carrier Tracking loops and increases the sensitivity. Further discussion of the same is done in the paper later.

LOOSE COUPLING: POSITION DOMAIN

A complementary filter (Brown, 1992) in feed forward mode is used for GPS-DR integration. A complementary filter is used to combine data from two independent noisy measurements of the same signal with complementary noise characteristics.

In this case, GPS solution has long-term stability but is characterized by large short term or high frequency noise. High short-term stability and a slow drift, which can be modeled as a low frequency error, characterize the DR system. These considerations make complementary filter an ideal fusion means for GPS-DR data.

A complementary filter structure is used to estimate various errors in GPS and DR using an appropriate Kalman filter (Gelb, 1974 Brown, 1992). Various parameters estimated using the Kalman filter and their characteristics are described below:

Gyro Bias Error

Gyro bias affects the measurements from the gyro at all times. Even when the vehicle is stationary, the gyroscope will read the bias value of angular velocity. This has an accumulative effect on heading and over time, the heading will drift away from its true value.

Gyro bias error becomes directly observable to the system when the vehicle is stationary or travelling in a straight line. Ideally, gyro bias should be constant over time, which can be modeled as a random constant but in reality, it is highly sensitive to the temperature variations. As a result, even a well calibrated system with a good initial estimate of gyro bias and scale factor cannot provide good estimate of position on its own for a long time. Therefore, a reasonable model for this error component will be a first order Gauss Markov process. The process noise is a function of the temperature change in the system during the sampling interval.

Gyro Scale Factor Error

Gyroscope scale factor affects the measurements only when the vehicle takes a turn. If the vehicle moves in a straight line, this will not have any effect on the heading. This doesn’t have an accumulative effect like bias as this error is introduced only during turns. This could be the potential source of heading error if the user continues to turn in loops in situations where GPS is unavailable (like in a covered parking lot).

Gyro scale factor becomes directly observable to a system when the vehicle takes a turn. Generally all gyroscopes have the same scale factor for clockwise and anti-clockwise turns. As a result, if a vehicle takes equal number of clockwise and anti-clockwise turns within a short span of time during which temperature variation is negligible, the heading error due to scale factor tends to be zero. The scale factor needs to be calibrated at the beginning and ideally would remain the same thereafter. But, similar to gyro bias, this also depends upon the temperature and therefore needs to be estimated regularly. Hence, a reasonable model for this error component will be a first order Gauss Markov process where the process noise is a function of the temperature change in the environment during the sampling interval.

Heading Error

Heading error consists of two components: bias error and scale factor error. Bias error has an accumulative effect on heading and the heading error grows with time if the bias error is non-zero. On the other hand, heading error due to scale factor error is a function of the heading change and hence it is equal to zero if there is no change in heading.

Heading error = Gyro bias error * time
+ Gyro scale factor error
* Heading change

As can be seen from the equation, if there is no change in heading, heading error rate depends only on the gyro bias error. There is no need to introduce additional noise in this state.

Odometer Scale Factor Error

Unlike gyro scale factor error, this affects the displacement of the vehicle whenever the vehicle is non-stationary. Therefore, it affects the measurements at all times as long as the vehicle is moving.

Additionally, unlike gyro errors, this doesn’t directly depend upon the temperature variation in the environment. Instead it depends upon the wear and tear of the tire, tire pressure variation (low frequency error) and vehicle speed (high frequency error). A reasonable model for this error would be a first order Gauss Markov process.

Velocity Error

Velocity error is a state variable in the integrated system which is affected by the odometer scale factor. Odometer pulse count provides information about the displacement of the vehicle, which is updated by the velocity measurements from the GPS. This state determines the error in the predicted velocity by using GPS derived velocity and taking into consideration all the error sources in velocity determination.

East and North Position Error

Errors in prediction of vehicle position in east and north direction are modeled using two states. The position is predicted using DR data and updated using measurements from the GPS derived position. These may be modeled as random walk processes with appropriate characteristics.

Shaping filters

Shaping filters are to be used to model correlated error in measurement data. In the GPS derived measurements, shaping filter is required for the following parameters:

a) Heading error
b) Velocity error
c) East position error
d) North position error

All these errors are modeled as first order Gauss-Markov process, the characteristics of which are described in the next sections.

Measurements

GPS derived heading, velocity and position are used as measurements to estimate the filter states in the system.

GPS Derived Heading

GPS derived heading is used as measurement to estimate some of the state variables namely, gyro bias, scale factor and vehicle heading. GPS heading error is a function of the SA error in doppler measurements for all the satellites used in velocity and heading computation. At low velocities when the SA range rate error is substantial compared to the velocity of the vehicle, the heading information from the GPS is almost useless.

GPS Derived Velocity

GPS derived velocity is used as measurement to estimate the velocity error in the integrated system. In a receiver, the velocity is determined from satellite range rate information, which is corrupted by non-white noise namely, SA. As a result, the GPS derived velocity has also non-white error in it, which needs to be modeled using shaping filters. Though modeling errors in each of the range rate measurements using shaping filters is a good possible solution, a simpler approach would be to model the overall affects of these range rate errors on velocity using a first order Gauss Markov process with desired characteristics.

GPS Derived Position

GPS derived position may be used to estimate some of the state variables in the filter, namely east and north position errors. Dominant error source for non-differential GPS derived position is SA whereas for differential GPS it is multipath effects. A good solution would be to model the range errors from each satellite using first order Gauss Markov process. However, that would require many states to be considered. An alternate approach is to assume that position errors have correlated noise due to SA and a function of DOP and can be modeled using a first order Gauss Markov process with desired characteristics.

TIGHT COUPLING

There is a large amount of literature on tight coupling as applied to INS for example Carroll (1977). However, very little has been said about tight coupling using DR. Here, the possibility of providing velocity aid to the carrier-tracking loop is explored. Since the code tracking derives aid from the carrier tracking and is considerably more robust, aiding of code lock loop is not considered in this paper.

The motivation behind tight coupling is to increase the availability of the navigation solution by increasing the sensitivity of the GPS receiver, which depends on the amount of noise present in the system. Noise power in the receiver depends on the bandwidth of the tracking loop filter. This bandwidth can be reduced during acquisition and tracking by utilizing the information from the DR sensors.

The doppler shift of a satellite signal in a receiver is due to the satellite dynamics and the user dynamics in the line of sight direction. The satellite dynamics is fairly smooth and can be computed from the rate of change of satellite position and the user dynamics can be estimated from the DR sensors in a GPS-DR integrated system. The projection of these dynamics in the line of sight direction can be computed from the satellite-user geometry.

The exact knowledge of the carrier frequency (doppler) reduces the search frequency range and hence the time required for signal acquisition. Theoretically, this improves the acquisition sensitivity by 2 dB (Kay, 1998). In practice, this can be achieved by storing the position estimate, gyroscope bias and scale factor, odometer scale factor along with satellite ephemerides and later using them to compute the carrier doppler. However this has a drawback that the DR sensor parameters especially the gyroscope bias changes with time and temperature.

Analysis of a Frequency Lock Loop (FLL)

In an FLL, reference oscillator vibration and Allan variance induced frequency jitter are small and negligible. The components that contribute to the frequency error significantly are thermal noise and dynamic stress (Ward, 1996). FLL 1-sigma tracking threshold is given by

$$\sigma = \sigma_t + 0.33 f_e \leq 0.0833 / T \quad (\mathrm{Hz}) \tag{1}$$

where

σ_t is the 1-sigma thermal noise frequency jitter (Hz)

f_e is the dynamic stress error (Hz) and

T is the pre-detection integration time.

The thermal noise frequency jitter is given by (Ward, 1996)

$$\sigma_t = \frac{1}{2\pi T}\sqrt{\frac{4FB_n}{C/N_0}\left[1+\frac{1}{T*C/N_0}\right]} \tag{2}$$

B_n is the Loop Bandwidth (Hz)

C/N_0 is the carrier to noise power ratio (Hz) and

F is 1 at high C/N_0 and 2 near threshold.

From Equation (2), it can be seen that the thermal noise frequency jitter is independent of the order of the filter. Either increasing C/N_0 or reducing loop filter bandwidth can reduce the frequency jitter. The aim of the tight coupling is to reduce the bandwidth as much as possible without affecting the dynamic performance.

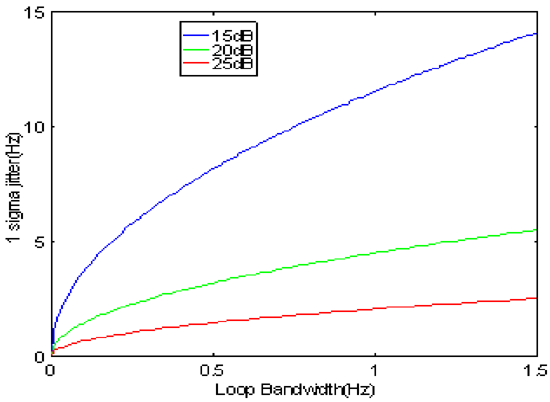

Figure 1: FLL thermal noise jitter with respect to the tracking loop bandwidth for various C/N_0 (T=0.01, F=1)

The frequency error due to dynamic stress is assumed to be a bias error. The error is given by (Ward, 1996)

$$f_e = \frac{1}{360*\omega_0^n}\frac{dR^{n+1}}{dt^{n+1}} \text{ (Hz)} \tag{3}$$

where

n is the filter order

ω_0 is the loop filter natural frequency (Hz) and

$\frac{dR^{n+1}}{dt^{n+1}}$ is the maximum line of sight jerk stress (degree/sec^3).

From Equation (3) it can be seen that the error is inversely proportional to the filter natural frequency, which in turn is directly proportional to the bandwidth of the loop filter. Also with higher dynamics the frequency error increases. When the tracking loop is unaided, there is a tradeoff between the thermal noise jitter and the allowed dynamics without loosing lock. If the tracking loop has to keep lock at high dynamics, it would require large loop bandwidth such that the dynamic stress related frequency error is small. However, that allows more thermal noise through the loop filter and the thermal noise frequency jitter becomes large.

With external aiding, the loop bandwidth can be reduced without compromising on dynamics. However, only the velocity, and not the acceleration or jerk, aiding is available from the DR sensors. A third, second and first order filters are sensitive to jerk, acceleration and velocity respectively. Therefore, a first or second order filter with reduced bandwidth is used when the tracking loop is externally velocity aided. In a second or third order filter, there will be a significant residual acceleration or jerk errors, which will limit the reduction of loop bandwidth.

The above discussion assumes that the clock has good stability. In case the clock has poor stability, then an additional term corresponding to the clock error has to be incorporated in the expression for FLL frequency jitter. This is independent of the loop filter bandwidth and hence a more serious source of error, which cannot be reduced by aiding.

Tight coupling Realization

If valid aiding is available from external sensors, the loop filter bandwidth can be reduced. This requires the receiver to be in loose coupling mode until the DR sensors are calibrated. When the aid is available, the order and/or the bandwidth of the loop filter can be changed as suitable for tight coupling. The doppler is estimated from the satellite ephemeris, clock frequency offset, user position estimate and user velocity. Pseudorange is estimated from the estimated position from DR, clock frequency offset and clock phase error. These values are used in the carrier lock loop and code lock loop with reduced bandwidth depending upon the accuracy of estimates in the external aiding and clock stability.

Presently, the doppler is estimated from the external aiding once in 10ms. For higher dynamics (i.e., larger acceleration and jerk stress), the aiding has to be at a higher rate as odometer gives only velocity output. Otherwise the bandwidth has to be increased to cater for higher uncertainty in the acceleration and jerk.

TEST SETUP

The test setup consists of a GPS core based on ADSP21060, a floating point DSP from Analog Devices. This module is interfaced to a Murata Rate Gyroscope via a 12 bit ADC and a standard odometer. The gyroscope is aligned to the vehicle axis through physical inspection. The output of the gyroscope is sampled at a rate of 100Hz and averaged over a period of one second for loose coupling. Similarly, the odometer pulses are accumulated for one second. In loose coupling mode, the integration of information from the sensors is performed at a rate of 1 Hz, which is quite adequate for automobile applications. The integration software resides inside the processor's on-chip memory. The data was collected in a Suzuki mini van and processed offline. The data was collected in an open environment with minimum obstruction to satellite signals.

The sensor data-sampling rate is the same for tight coupling, but the averaging time and accumulation times for gyroscope and odometer respectively are reduced to 10 ms so as to reduce the latency.

TEST RESULTS

Loose Coupling

Figure 2 shows a trajectory of a field trial from the GPS derived position using a dark shaded line. The light shaded line corresponds to the integrated GPS-DR trajectory. It can be seen that both the trajectories almost overlap in most places.

Satellite blockage was simulated by making the GPS derived position unavailable between the points A and B. This segment of the route is highlighted in the Figure 3. The satellite blockage period was 100 seconds during which the vehicle traveled a distance of 1.6 km.

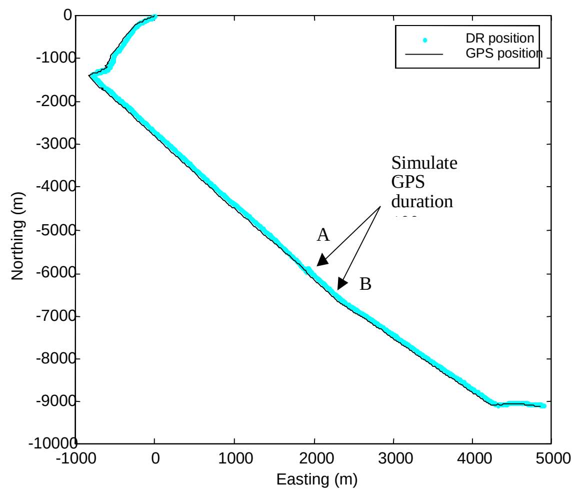

Figure 2: Trajectories of GPS derived position and GPS-DR derived position in field trial 1

The trajectories of GPS and integrated GPS-DR solutions for a sample data set is shown in figure 2. It can be seen that the errors between the two trajectories are negligible until the GPS solution is disabled.

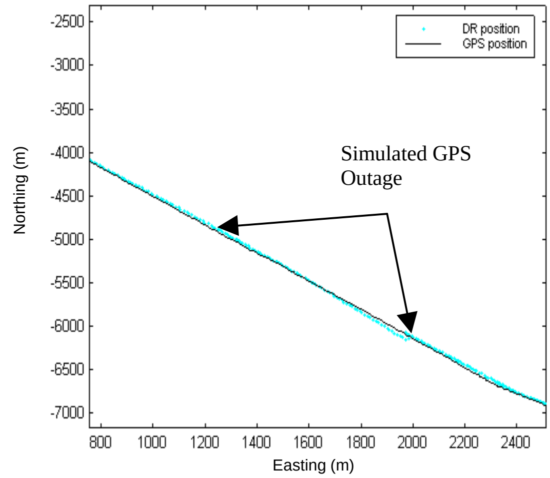

Figure 3: Cross track error growth during simulated GPS outage in a section of the route in field trial 1.

During the satellite blockage, the position solution was computed from DR. After 100 seconds of GPS outage a cross track error of 60m was found, which corresponds to 3.8% of the distance traveled. The error in the estimate of sensor bias and scale factors caused an error growth during the GPS outage. Once the GPS derived solution became available, the GPS-DR position closely followed the GPS trajectory.

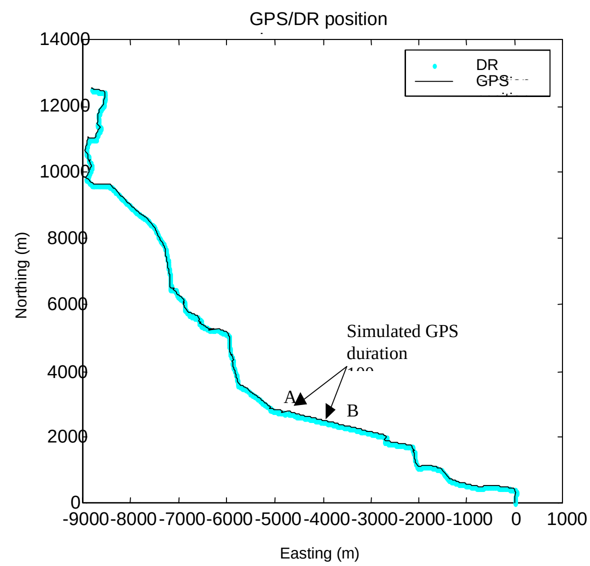

Figure 4: Trajectories of GPS derived position and GPS-DR derived position in field trial 2

Figure 4 shows the GPS and GPS-DR trajectories for a different field trial using dark and light shaded lines respectively. Once again GPS outage has been simulated between the points A and B for a duration of 100 seconds. The total distance traveled during this time period was 930m.

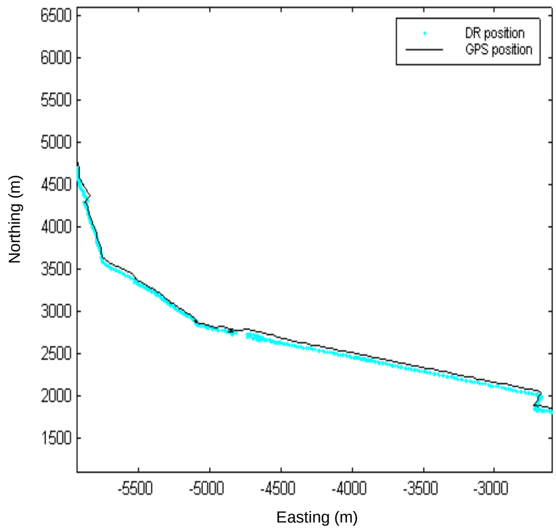

Figure 5: Cross track error growth during simulated GPS outage in a section of the route in field trial 2.

Figure 5 shows the GPS outage section of the field trail trajectory. It can be seen that once again there is an error growth due to residual sensor errors. After 100 seconds of GPS outage a cross track error of 80m was found, which corresponds to 8.6% of the distance traveled.

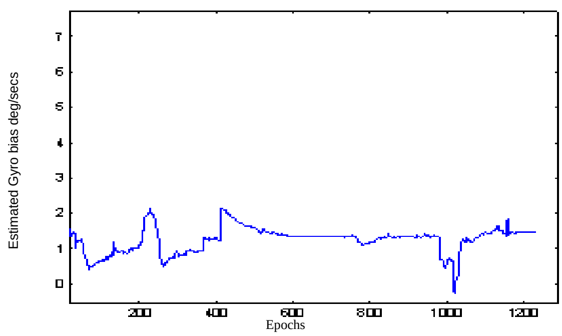

Figure 6: Estimated gyro bias during field trial 1

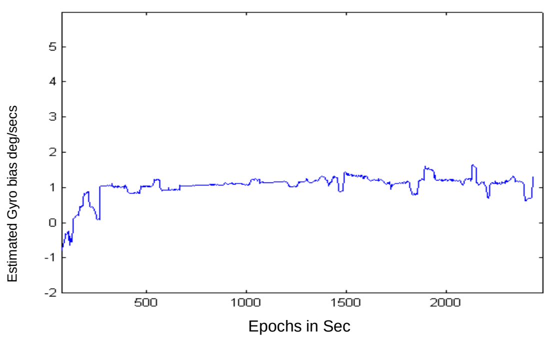

Figure 7: Estimated gyro bias during field trial 2

Figures 6 and 7 show the estimated gyro bias during the entire duration of the first and second field trials respectively. The gyro bias variation up to 2^0/sec was found during those periods, which is well within the specification of the used gyro sensor.

Table 1 shows the effect of GPS blockage at various sections of the field trials and corresponding cross track error . On an average of 5.3% error growth was observed.

Section	Simulated GPS outage duration (s)	Distance traveled during outages (m)	Cross track error (m)	% cross track error as a function of distance traveled
1	100	1600	60	3.8
2	100	930	80	8.6
3	100	1300	45	3.5
4	200	2500	130	5.2

Table 1: Cross track error during GPS blockage at different sections of the field trial route

Tight Coupling

A second order FLL was simulated with and without carrier aiding and with random acceleration. Initially, the loop bandwidth was chosen to be 1.0 Hz. Figure 8 shows the variation of doppler with this loop bandwidth.

The FLL carrier was then aided externally and the loop bandwidth was reduced to 0.1 Hz. The doppler variation with this reduced bandwidth is shown in Figure 8 with a dark shaded line. It can be seen that with external aiding, the doppler variation is much smaller in magnitude.

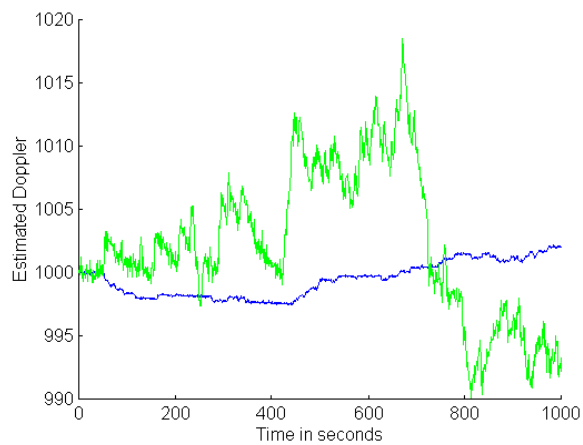

Figure 8: The variation of carrier doppler with and without aiding for a second order filter at a C/N0 of 10dB-Hz

Figure 9 shows the practical reduction of bandwidth under low dynamics for a second order loop filter with a loop bandwidth of 1.2Hz. The satellite doppler offset was computed in the carrier lock loop (Rambo (1989)). The power spectrum of the carrier doppler offset without aid is shown in green and with aid is shown in blue.

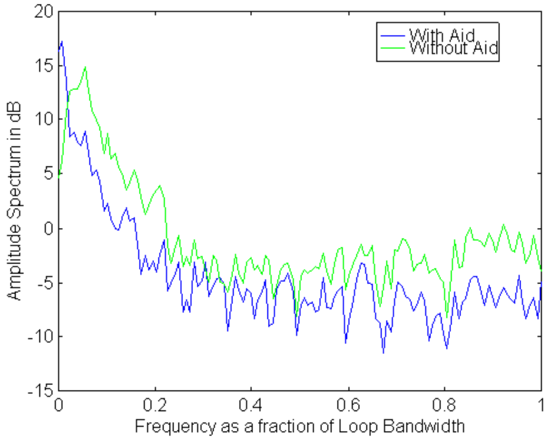

Figure 9: power spectral density of carrier doppler offset with and without aiding at low dynamics

At higher dynamics, the senescence of the DR data should be considered before use. The pre-detection integration period may have to be reduced. From the Figure 9, it can be seen that there is around 3dB improvement in tracking sensitivity for low dynamic situations. During reacquisition, the exact knowledge of the doppler yielded an improvement of 2dB in sensitivity during the field tests.

CONCLUSIONS AND FUTURE WORK

An integrated system consisting of a NAV 2000 GPS receiver from Accord, a low cost piezoelectric vibrational gyro from Murata and a standard odometer was developed. Field trials were performed with this system and the data were processed offline. GPS outages were simulated at various sections of the field trials and an average cross track error growth of 5.3% of the distance traveled was found.

Tight coupling of the GPS and DR sensors were tested by external carrier aiding to the receiver FLL. It was found that the receiver's tracking sensitivity improved by 3 dB by the aiding. Similarly, the acquisition sensitivity also improved by 2 dB due to external aiding.

However, the system has to be well integrated and proper synchronization of DR data collection for aiding at higher rates has to be achieved. Since the FLL itself is mildly sensitive to dynamics, lower quality sensors can be used without much degradation in performance.

To assess the absolute performance improvements, the results have to be verified against a true reference such as a digital map. The improvement in the reliability of the solution in both loose coupling and tight coupling mode by using DGPS is yet to be studied.

REFERENCES

Eric, A and D. Powell (1995), "An Examination of the Relative Merits of Various Sensors for Land Navigation", *Proceedings of the ION GPS-95*, Palm Springs, California, September 17–20, pp 1269-1282.

Brown, R.G. and P.Y.C.Hwang (1992), "Introduction to Random signals and applied Kalman filtering", *second edition, John Wiley and Sons Inc., 502 pp.*

Kim, J, J.G.Lee, and T.K.Sung (1996), "Compensation of Gyroscope errors and GPS/DR Integration", *IEEE-PLANS*, pp. 464-470.

Ren, D and G. Dedes, (1995), "Nonlinear smoothing of Dead Reckoning Data With GPS Measurements", *Proceedings of the ION GPS-95*, Palm Springs, September 12-15, pp 1285 – 1294.

Weisenburger.S and C. Wilson (1999), "An Integrated Vehicle Positioning System for Safety Applications", *ION NTM-99, Jan 25-27*, San Diego, pp 361 – 368.

Carrol, R.W and W.A.Mickelson (1997), "Velocity Aiding of Noncoherent GPS Receiver", *IEEE-NAECON-77,Dayton*,Ohio

Kay, S (1998) "Statistical signal processing-detection theory", *Prentice Hall.*

Kriegsman. A.B, D.B.Cox, Jr., and W.M.Stonestreet (1997), "An IMU-Aided GPS Receiver", *Proceedings of the 33 Annual Meeting of ION*, Costa Mesa, California, June 22 – 24. Archives P-490, 50 pp.

Accord Software & Systems Pvt. Ltd.(1998), "NAV-2000,Evaluation Kit, User's Guide", *Revision 1.0.127*

Ward, P (1996), Satellite signal acquisition and tracking, Chapter 5, "Understanding GPS: Principles and Application", *Artech House Publishers, Boston, MA, 1996.*

Geier.G.J (1998),"GPS Integration with low cost sensor technology for automotive Applications", *Lecture notes for course conducted during August 10-21,1998, University of Calgary*

Rambo, J.C (1989),"Receiver Processing Software design of the Rockwell International DoD standard GPS Receivers", *ION GPS –89*.

Gelb, A (1979),"Applied Optimal Estimation", *MIT Press*, Massachusetts Institute of Technology, Massachusetts, Cambridge, 374 pp.