Development and Testing of a Real-Time GPS/INS Reference System for Autonomous Automobile Navigation

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BIOGRAPHIES

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ABSTRACT

Precise position and velocity information have already led to a large number of vehicle-based applications. Access to this information in real-time further opens the door to telematic applications such as en-route navigation assistance. This paper deals with the development of a real-time system to be used for the testing of proposed autonomous automobile navigation systems, whereby the driver need not actually control the vehicle. From a navigation standpoint, this requires not only very precise but also very reliable position and velocity information with high availability and low latency. These constraints are even more stringent for a reference system, whose solution is to be considered ideal, as is the case here. To this end unaided GPS is insufficient, as it does not provide the necessary availability or reliability. A loosely integrated approach using a GPS Real-Time Kinematic (RTK) and mid-level INS is therefore proposed to alleviate these problems.

Given the time-critical nature of such an application, emphasis is given to the real-time aspect of the system. An implementation is presented whereby IMU data are

processed as they are received and INS states are updated with inherently latent GPS data. The objective of this paper is to assess the accuracy and feasibility of such a system, which is based on the Honeywell HG-1700 IMU and the NovAtel OEM4 GPS receivers.

A vehicle test was performed under varying operational conditions, including open sky, and areas where shading is encountered due to buildings, foliage and overpasses. System performance is evaluated through the accuracy of the INS only solution during periods of simulated GPS outages. Initial testing shows the system is able to bridge short GPS data gaps (1 to 5 seconds) with decimeter level accuracy under mild vehicle dynamics. Increased vehicle dynamics combined with longer GPS outages currently produce INS errors at the meter level.

INTRODUCTION

The Global Positioning System (GPS) and Inertial Navigation Systems (INS) have long been known for their effective use as standalone navigation systems. Further, their integration has led to high-accuracy estimates of position, velocity and attitude. It is this high accuracy that is opening the door to a wider variety of vehicle-based applications.

This paper deals with the development of a real-time system to be used for the testing of proposed autonomous automobile navigation systems, whereby the driver need not be in complete control of the vehicle. From a navigation standpoint, this requires not only very precise but also very reliable position and velocity information with high availability and low latency. These constraints are even more stringent for a reference system, whose solution is to be considered ideal, as is the case here. To this end unaided GPS is insufficient, as it does not provide the necessary availability or reliability. A loosely coupled integration approach using a GPS RTK and mid-level INS is presented herein. The real-time requirement of such a system is given emphasis because of the time-critical nature of the application.

The objective of this paper is to present a method of integrating GPS and INS information in a real-time environment with as little latency as possible. Therefore, an implementation is presented whereby Inertial Measurement Unit (IMU) data are processed as they are received and INS states are updated with inherently latent GPS data. An assessment of the accuracy and feasibility of such a system, based on the Honeywell HG-1700 IMU and the NovAtel OEM4 GPS receivers, is presented.

The paper begins with a brief look at the methods used in the development of the system. Again, emphasis is given to the real-time requirements. The field test used to evaluate the system is described and an assessment of the system is made.

BACKGROUND

High-accuracy vehicle navigation has significantly benefited from developments of the Global Positioning System (GPS). In particular, the use of carrier phase based positioning methods has allowed for centimetre to decimetre level positioning. The largest limitation of GPS however, is the line-of-sight requirement that is compounded by a low signal power at the antenna. This leads directly to reduced signal and position availability at best, or erroneous positions at worst.

To help alleviate these problems, much research has been directed at the integration of GPS with an INS. The complementary nature of these two systems makes them ideal for integration in a common positioning system [Greenspan, 1994]. However, most research to date has focused on the use of high quality IMUs. Although these allow for good navigation performance, their economic offset is a serious limitation. Lower cost, and therefore poorer quality IMUs must therefore be investigated as possible alternatives. Investigations by Salychev et al. [2000], Wolf et al. [1996], Schwarz and Zhang [1994] and Yang et al. [2000], to name a few, have used low-cost IMUs although not for high accuracy navigation.

METHODOLOGY

This section outlines the basic methodology associated with this work. It begins with a discussion of integration options and details the final system. A discussion of how to implement the real-time requirement is then presented.

System Integration

Several approaches are possible for an integrated GPS/INS system. The primary variable often relates to which information is shared between the GPS and INS components (tight versus loose integration). In the tightly integrated approach, raw pseudorange, carrier phase and/or range rate information is used to update the INS filter. In contrast, a loosely coupled approach uses GPS position and velocity updates only. In this regard, it suffers from the requirement of viewing four or more satellites before a position fix can be computed, thus leading to longer time intervals between updates of the INS filter.

The software used herein is the fusion of two software packages. First, FLYKIN™ is a carrier phase based software package using on-the-fly (OTF) ambiguity resolution for static and kinematic positioning applications developed at the University of Calgary. Second, GAIN2™ integrates GPS position and velocity information with IMU data and was co-developed by the University of Calgary and Bauman Moscow State Technical University.

A loosely coupled approach was used here, primarily motivated by the origin of the integrated software. A loosely coupled system was straightforward to implement given that the GPS position and velocity estimates were readily available from the FLYKIN™ component of the software. In this regard, the GPS filter is updated with double difference pseudorange, carrier phase and Doppler (i.e. range rate) measurements. A combination of the FASF [Chen, 1994] and LAMBDA [Teunissen and Tiberius, 1994] methods are used for ambiguity resolution on-the-fly. L1 and L2 measurements are used in the filter, if available. In this case, the widelane ambiguities are resolved before an attempt to handoff to the L1 ambiguities is made. The inertial part of the software estimates the necessary INS error states, including position, velocity, attitude and some sensor level errors.

Real-Time Issues and Software Implementation

As previously mentioned, the time-critical nature of autonomous driving applications requires that vehicle information be available with as small a latency as possible. Unfortunately, this imposes a severe constraint on the integration software. The primary reason for this is that the GPS measurements received from a GPS receiver are typically latent with respect to the IMU data. The latency can be expected to be as large as half of a second [Fenton, 2000]. In other words, a GPS measurement may be received by the logging computer with a time tag that is up to 0.5 seconds behind the last received IMU measurement. This time difference is crucial since timing errors between sensors can play a major role in system performance.

In a loosely coupled system, this GPS/INS time offset is further compounded by the time required to process the GPS data before passing the position and velocity information to the INS filters. In particular, the ambiguity search algorithm must be very efficient. Results from the test performed indicate that a time offset between the IMU and the GPS updates of a few tenths of a second is typical.

There are two methods of dealing with this problem. The first approach buffers the IMU data until the appropriate GPS measurements are received. Once received, the IMU and GPS data are processed as if they were received in the proper sequence. This can be considered a pseudo-real-time approach with the main drawback being the time lost waiting for the GPS measurements. For example, if the GPS latency is 0.2s and the vehicle is traveling at 30m/s (~110km/h) then the vehicle will move six metres while buffering the IMU data.

Instead, the approach adopted here processes the IMU data as it is received. However, the IMU data is buffered in memory as it is processed. Similarly, the INS solutions are also stored. Then, when a GPS update is ready, it can be applied to the appropriate INS solution, according to the GPS time tags. It is then a matter of processing the IMU measurements from the time of the GPS measurement to the current time in order to get the most updated position. In this way, the most current position is always the INS solution predicted from the last GPS update. Figure 1 gives a graphical representation of the updating process.

System Performance

Given the processing scheme adopted here, the accuracy of the integrated system is dependent on two things. First, the accuracy of the GPS RTK solution will define the absolute accuracy of the system. Second, the relative accuracy of the INS will then determine how this initial GPS error is propagated forward in time. Mathematically, the real-time positioning error can be expressed as:

$$\sigma_{RT}^2 = \sigma_{GPS}^2 + \sigma_{INS}^2(t) \quad (1)$$

where:

σ_{RT}^2 is the real-time position error variance

σ_{GPS}^2 is the GPS position error variance

$\sigma_{INS}^2(t)$ is the INS prediction error variance as a function of time

The accuracy of the GPS solution is fairly well known. Floating ambiguity solutions can provide decimetre accuracy while fixed integer solutions are capable of centimetre accuracy over short baselines [Cannon, 1997]. To quantify overall system performance, it therefore becomes important to analyze the INS errors over time. This will be discussed in the next section.

DATA COLLECTION AND PROCESSING

Equipment

The IMU used here is a Honeywell HG-1700, which is considered to be a medium-level accuracy unit. The gyro specifications for the unit, which play the largest role in performance, are presented in Table 1.

Table 1 - HG-1700 Gyro Specifications

Parameter	Value
Run to run (turn-on to turn-on) stability	0.5 - 1 deg/h
In run stability	0.3 - 0.8 deg/h

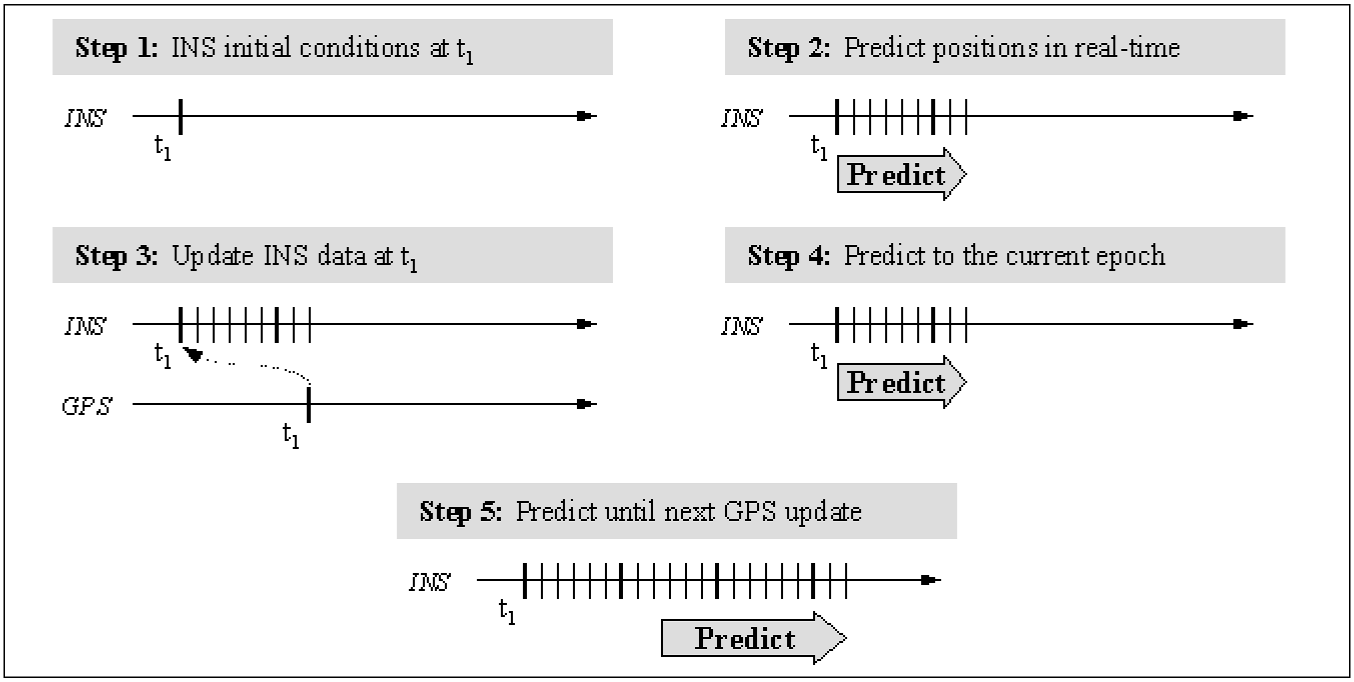

Figure 1 - Graphical Description of how to Update the INS with Latent GPS Data

The GPS base station receiver was a dual-frequency NovAtel OEM3 Millennium card. The vehicle (rover) was equipped with a NovAtel Black Diamond receiver. It contains an OEM4 card capable of measuring dual-frequency data. The receiver also acts as an interface to the IMU, receiving and time-tagging the data with GPS time before outputting it to a serial port.

Field Test

The data analyzed herein was collected in Palo Alto, California on February 21, 2001. The vehicle employed was the DaimlerChrysler test vehicle, a modified Mercedes Benz E420. The IMU was mounted on the center console in the backseat of the vehicle. Raw IMU data was logged at 100Hz and dual-frequency GPS data was logged at 1Hz. Both the GPS and IMU data were logged through a single serial port on a laptop computer. IMU data was processed at only 10Hz.

The field test was performed to encompass a variety of operational conditions. The vehicle trajectory relative to the starting position is shown in Figure 2. The trajectory began by turning south on Page Mill Road merging onto I-280. The vehicle turned around at Sand Hill Road using a cloverleaf. The vehicle then proceeded back to Page Mill Road before finishing. Vehicle velocities varied from stationary to over 100 km/h. The total elapsed time of the test was about 28 minutes.

Conditions experienced during the test varied from mild signal masking due to small buildings and trees along Page Mill Road to a combination of open sky and overpasses on the Interstate. This represents a good spectrum of environments for initial testing of the system. Furthermore, initial production systems will not likely be capable of autonomous driving in severe urban environments, which are not represented here.

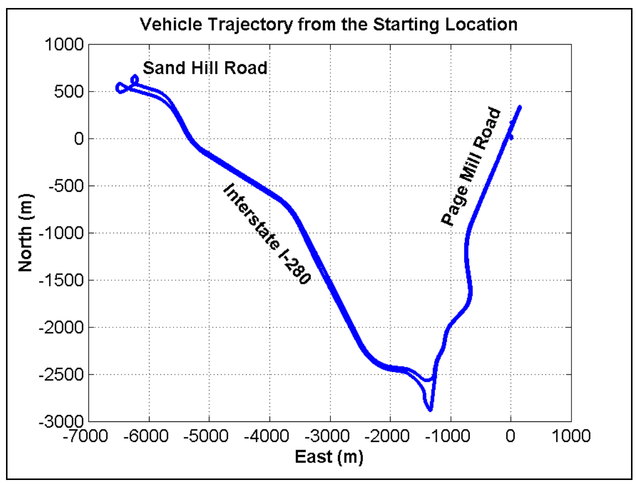

Figure 2 - Vehicle Trajectory

Data Processing

Real-time processing of the data was performed during data collection, although the results presented herein were obtained offline. However, offline processing was performed in a "playback" mode whereby real-time situations are approximated. In this regard, the GPS/INS time offset discussed above will be the most important parameter. The GPS/INS time offset observed for the offline test was similar to what is experienced in a real-time environment.

To analyze the prediction accuracy of the INS, it is desirable to have a truth trajectory with which to compare. Unfortunately, such a trajectory was not available here so a different approach whereby GPS data outages are simulated was used. The idea is that if a GPS/INS solution is computed using all available GPS data, it can be considered as a reference trajectory. When the data is then processed with simulated GPS data gaps, the resulting trajectory will differ from the reference trajectory only during those times. A comparison of the solutions computed with and without the GPS data gaps will thus provide an estimate of the INS prediction accuracy. Further, by simulating data gaps of varying duration, an estimate of the INS prediction error as a function of time (i.e. the second term on the right hand side of equation 1) can be estimated, which is a major factor in the overall system performance. The objective here is not to obtain a statistically significant representation of this function, but to illustrate the general system performance under varying operational conditions.

DATA ANALYSIS

Figure 3 shows the number of satellites (double differences plus one) and the ambiguity state as a function of time for the entire test. As is evident, this test is not ideal from a GPS point of view. However, it represents a worst-case environment in which to test the system.

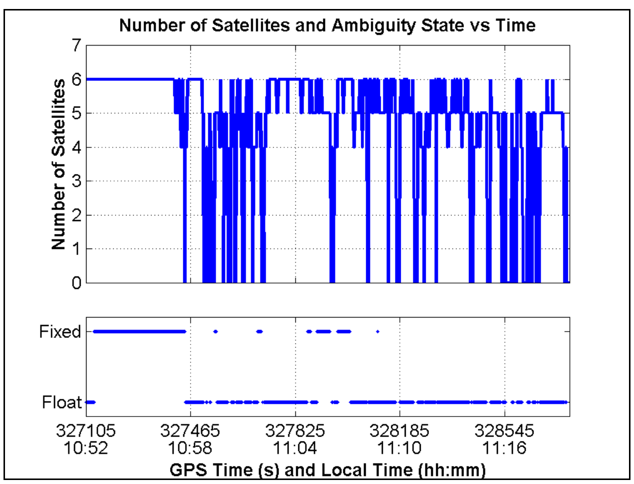

Figure 3 - Number of Satellites and Ambiguity State Versus Time

Unfortunately, the worst-case scenario somewhat hinders the analysis capability. Specifically, to obtain the most accurate reference trajectory, the GPS data gaps should be simulated during periods when a fixed ambiguity solution is available. In this case, due to the lack of satellite availability, there are very few periods where this occurs for extended periods of time.

To eliminate this problem, periods of float ambiguities were also used for determining the reference trajectory. When doing this, care must be taken to ensure the float solution is sufficiently converged so that it produces smooth trajectory estimates. If this condition is met, the reference trajectory will be smooth, although possibly biased slightly. However, since we are ultimately looking at the difference between the two trajectories, this bias will disappear, leaving the INS prediction errors. Figure 4 shows horizontal INS prediction errors computed over the same time interval, once using fixed and the other using floating ambiguities for the reference trajectory.

As can be seen, the results appear slightly better when using the float ambiguities for the reference trajectory than when using the fixed ambiguities. Although this may seem strange, this is to be expected. The reason is the way in which the reference trajectory is generated. To this end, consider the reference trajectory as being the weighted average of the GPS only and INS only solutions. With fixed ambiguities the reference trajectory will follow very closely the GPS solution, due to its high accuracy. However, with the float ambiguity solution, the reference trajectory will not follow the GPS solution as closely because of the degraded accuracy of the float ambiguity position estimates, relative to the fixed ambiguity case. In other words, for the float ambiguity case the INS only solution will be given more weight in the generation of the reference trajectory. Consequently, when the GPS data gap is simulated, the resulting INS only solution should follow more closely the reference trajectory than in the fixed ambiguity case (where the reference trajectory followed the GPS only solution very closely).

Theoretically, therefore, the INS prediction accuracy analysis performed here will be slightly optimistic. However, given that the differences between the fixed and float ambiguity approaches are fairly small (see Figure 4), this is tolerable.

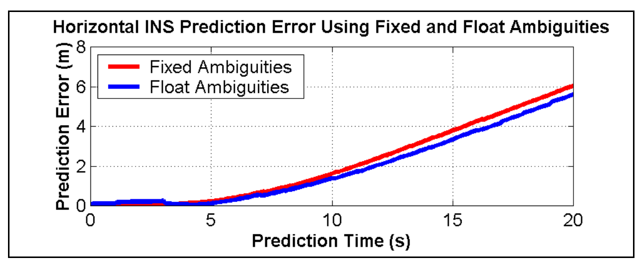

Figure 4 - Horizontal INS Prediction Error Using Fixed and Float Ambiguity Reference Trajectories

In total, six different data gaps were used, each simulated separately. All six are shown in Figure 5 and are labeled A through F. All gaps are labeled on the side of road on which they are simulated. Note that gaps A and B overlap. The results in Figure 4 correspond to Gap A.

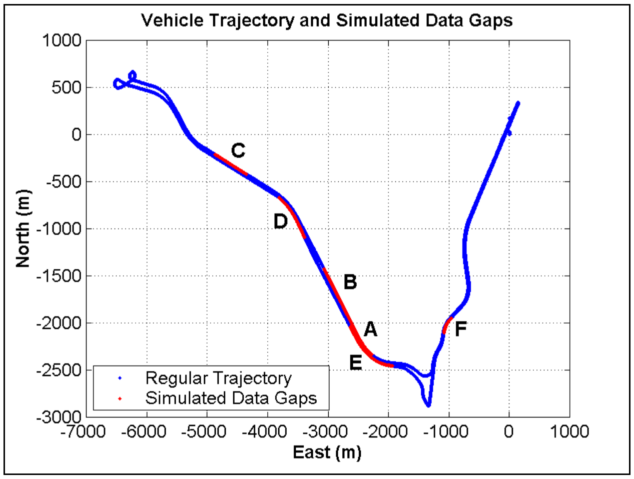

Figure 5 - Vehicle Trajectory with Locations of Simulated Data Gaps (Labeled A through F)

Figures 6 through 11 show the north, east and combined horizontal (labeled as "2D") error for each of the different data gaps of Figure 5. A plot showing the trajectory during the data gap is also shown in each figure. The origin of the trajectory plot corresponds to the start of the simulated data gap. Vertical prediction errors are not shown since they are often not of great concern in vehicle-based applications.

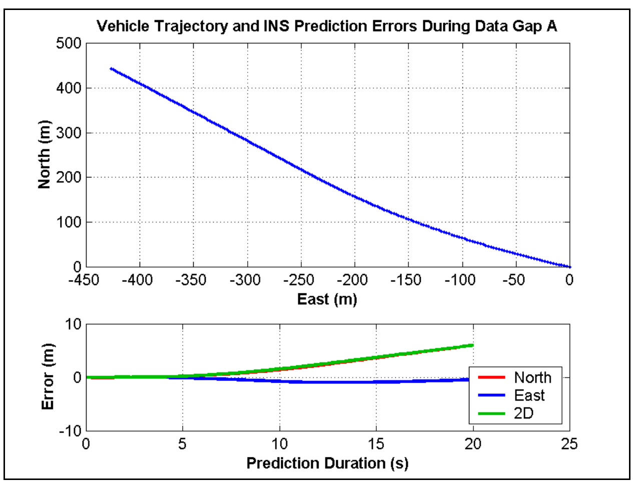

Figure 6 - Vehicle Trajectory and INS Prediction Errors During Data Gap A

Upon closer inspection of the various cases, it becomes obvious that the position error appears to be related to the dynamics of the vehicle. When the vehicle undergoes cornering, the INS prediction becomes poorer. Furthermore, it is not until the cornering maneuver is started that the prediction errors begin to increase at a fairly rapid rate. This phenomena is well known with inertial systems, as explained in Jekeli [2000], for example.

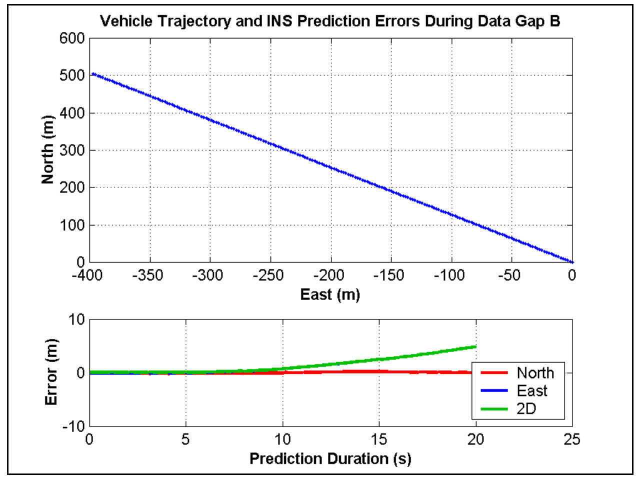

Figure 7 - Vehicle Trajectory and INS Prediction Errors During Data Gap B

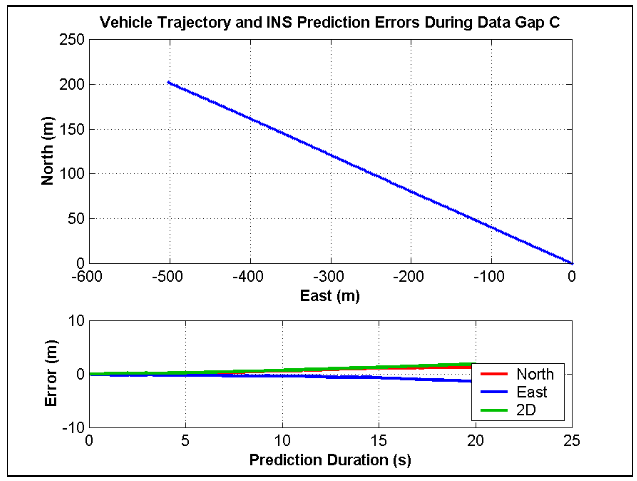

Figure 8 - Vehicle Trajectory and INS Prediction Errors During Data Gap C

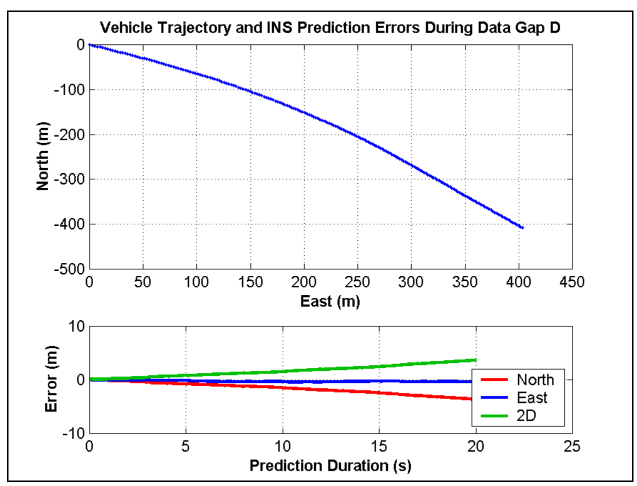

Figure 9 - Vehicle Trajectory and INS Prediction Errors During Data Gap D

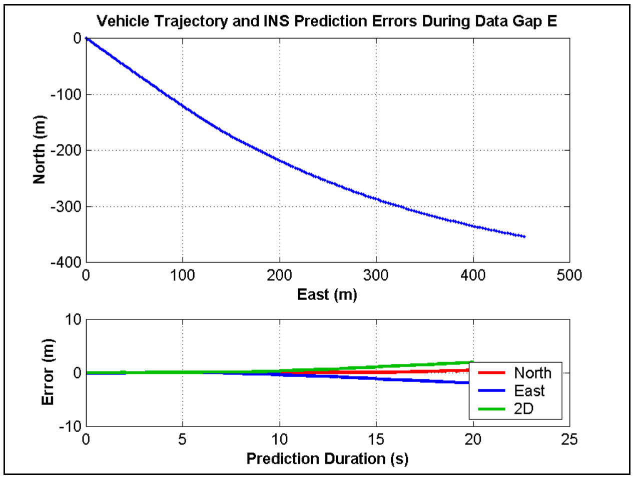

Figure 10 - Vehicle Trajectory and INS Prediction Errors During Data Gap E

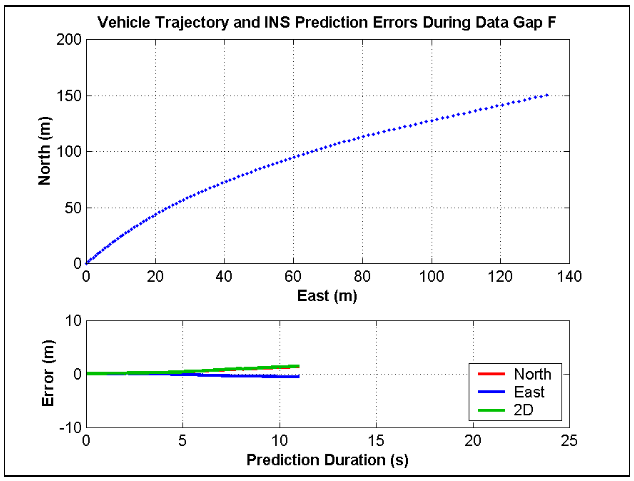

Figure 11 - Vehicle Trajectory and INS Prediction Errors During Data Gap F

Given the conditions under which the test was performed, the results obtained here are very promising. The mean and median horizontal errors are shown in Table 2 and are reproduced graphically in Figure 12.

If the extended data gaps are not considered, the system is capable of predicting positions to an accuracy of a few centimetres over one second. Assuming fixed ambiguities, this is the expected accuracy of the system under ideal open sky conditions (i.e. with no data gaps). In contrast, under signal masking environments, with data gaps of up to five seconds, the prediction accuracy is typically better than a few decimetres. For longer time periods, metre level accuracy is expected. However, if one considers autonomous driving in fairly benign environments, such as on freeways or in sub-urban areas, a data gap of longer than a few seconds is quite unlikely. It seems therefore, that the proposed system would be ideal under these circumstances.

Table 2 - Mean and Median INS Horizontal Prediction Errors as a Function of Prediction Duration

Duration (s)	Mean (m)	Median (m)
1	0.08	0.07
2	0.14	0.11
3	0.18	0.16
4	0.26	0.16
5	0.34	0.25
6	0.44	0.38
7	0.58	0.54
8	0.70	0.70
9	0.85	0.86
10	1.04	1.03
11	1.23	1.07
12	1.46	1.37
13	1.72	1.78
14	1.98	2.16
15	2.23	2.45
16	2.50	2.69
17	2.79	3.01
18	3.07	3.23
19	3.38	3.44
20	3.68	3.67

Furthermore, if one considers using the INS position as a position seed to the GPS filter (as discussed in Scherzinger [2000], for example), a prediction accuracy of a few decimeters should allow for direct acquisition of the widelane ambiguities, assuming the position accuracy prior to the data gap was sufficiently high. In fact, this approach was used in the generation of the GPS information shown in Figure 3. Without this feedback from the INS the number of fixed ambiguity positions decreases significantly from 31% to 23% of the total number of epochs. Typically, one would expect greater improvements than this. However, the poor satellite geometry experienced here will have played a play a major role in this regard.

Finally, in some cases, the velocity errors may also be of interest. Performing an analysis similar to the one presented above but in the velocity domain shows that the INS is capable of predicting the horizontal velocity with a mean error of less than 30cm/s for data gaps up to 20 seconds.

CONCLUSIONS

This paper presented a GPS/INS system capable of acting as a reference system for autonomous driving applications. Emphasis was given to the real-time aspect of the system and a method of dealing with the inherent latency of the GPS data was discussed in detail.

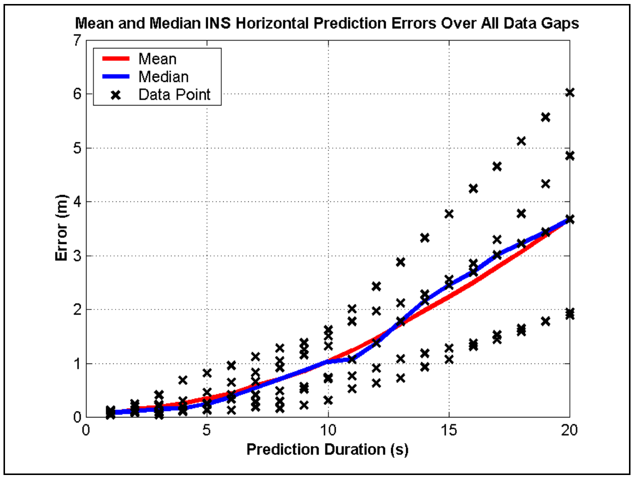

Figure 12 - Mean and Median INS Horizontal Prediction Errors

A field test performed under a variety of operational conditions showed the system is capable of delivering position accuracies on the order of a few centimetres in real-time under ideal conditions. Under signal masking environments, accuracies better than half a metre can be expected for GPS data gaps of up to about seven seconds, depending on vehicle dynamics. However, for autonomous driving in relatively benign environments such as on freeways or in sub-areas, GPS data outages of more than a few seconds are unlikely.

Finally, the test analyzed here was very poor from a GPS standpoint. As such, it represents a worst-case scenario and performance will improve under more ideal GPS environments.

FUTURE WORK

Future developments on this project will involve looking at using less stringent data selection criteria. Currently, several GPS pseudorange observations are being rejected due to loss of carrier phase lock. Moving away from this conservative approach should reduce the number of long-term GPS data outages and accordingly, limit the position error variance to the metre level.

A tightly integrated approach will also be investigated. The current loose integration suffers from the requirement of viewing four or more satellites in order to compute a position and velocity update. A tighter integration should improve results during periods where three or fewer satellites are visible.

Finally, comparison of the estimated positions with digital map coordinates will allow for an independent assessment of system accuracy.

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