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Performance Comparison for Vehicle Tracking in Urban Areas: GPS/INS Integrated System vs. GPS Alone

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ABSTRACT

The Global Positioning System (GPS) is a worldwide radio-navigation system widely used for tracking tasks in transportation and other fields. In an urban area, where there is a high density of population and transportation activity, many kinds of vehicles, such as buses, taxis, police cars, and vehicles with Hazardous Materials (HAZMAT), need to be accurately tracked in real-time for fleet management or security purposes. Although GPS is excellent in its availability, scope, and precision under ideal circumstances, such as in the air, it does not work well when the receiver is under or near canopies such as trees, high-rise buildings, or tunnels. One effective solution is to integrate the GPS with other tracking systems, such as the Inertial Navigation System (INS). INS relies on no external references after it is initialized and aligned, but its positioning error increases without limit as time goes by. This paper describes our research findings on the performances of a GPS/INS Integrated System and a GPS for vehicle tracking in urban areas. Performance is measured by both positioning accuracy and location data update frequency in our study. Our analysis using the field-test data shows that the GPS/INS Integrated System has much smaller location error than the GPS alone and guarantees the location data update frequency. The GPS/INS Integrated System is a reliable tracking technology for accurately tracking vehicles in urban areas.

1. INTRODUCTION

The Global Positioning System (GPS) is a worldwide radio-navigation system enabled by a constellation of at least 24 operating satellites and their ground stations. GPS provides specially coded satellite signals that can be received and processed by GPS receivers. These satellite signals enable a GPS receiver to compute position, velocity, and time from almost anywhere on or near the earth .

GPS, mainly used for vehicle positioning, can be found in many transportation applications. Automatic Vehicle Location (AVL) systems have increasingly gained attention for fleet management and emergency response. Transit AVL systems are one example area where vehicle-tracking technologies have been implemented in the U.S. According to a report by the Transit Cooperative Research Program, most transit AVL systems in the U.S. use GPS for vehicle tracking [5]. Modern emergency vehicles have also equipped GPS receivers for fast positioning and efficient dispatch. GPS has been widely used for vehicle tracking in other systems as well. In a travel time study by Quiroga and Darcy [4], GPS was used to automatically collect time, location, and speed data of test vehicles.

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After being properly filtered and aggregated, these data were used for further applications such as the Geographic Information System (GIS) based management information systems. The real-time tracking of "probe vehicles" is critical for the Intelligent Vehicle Highway Systems (IVHS) [7]. It was found that GPS provided useful data for vehicle tracking, although the performance of GPS varies under different working conditions, e.g., the GPS performance becomes worse when GPS is working on downtown streets. Another popular application using GPS-based vehicle tracking technology is anti-theft. A recent survey found that one-third of consumers want a vehicle-tracking application that will help recover their vehicles in case of theft [2]. In light of the tragic events of September 11, 2001, enhancing the security of our transportation system is expected to be one of the highest priorities for transportation agencies. Vehicles should be efficiently tracked in real-time, and GPS is considered the first choice for such tasks.

Although GPS is excellent in its availability, scope, and precision under ideal circumstances, such as in the air or on the sea, a GPS receiver cannot work well when it is not clearly visible from a certain number (four when the receiver is in 3D mode and three when in 2D mode) of GPS satellites [6]. Canopies (such as trees, buildings, and tunnels) block and reflect satellite signals, and a GPS receiver cannot determine its location when satellite signals are blocked. Furthermore, when satellite signals are reflected by canopies and take a longer time to reach a GPS receiver (which causes the "multipath" effect), the GPS receiver will report inaccurate locations.

In recent years, studies have been conducted on systems that integrate GPS with other tracking systems such as the Inertial Navigation System (INS). INS applies Newton's laws of motion to deduce the positions of a vehicle by measuring the accelerations the vehicle experiences as it travels. INS is comprised of an Inertial Measurement Unit (IMU) and one or more navigation computers. An IMU contains a cluster of two or more accelerometers and three or more gyroscopes that are rigidly mounted to a common base to keep the same orientations. The gyroscopes are sensors for measuring rotation, while accelerometers are sensors for measuring acceleration. INS does not rely on external references for navigation, but its mean-squared navigation errors increase with time.

The GPS/INS Integrated System is designed to work at almost any location on the earth. When there are no obstructions, the Integrated System relies on GPS to navigate; when canopies affect GPS significantly, which should not be a very long period for moving vehicles in urban areas, the Integrated System will turn to the INS for navigation. The GPS and INS are typically integrated with the Kalman Filter, which is an effective and versatile procedure for combining noisy sensor outputs to estimate the state of a system with uncertain dynamics [1].

To quantitatively evaluate the performance of the GPS/INS Integrated System, a field test was performed. The objective of the test was to evaluate the difference in performance between the GPS/INS Integrated System and the GPS alone under different canopy levels in urban areas for vehicle tracking. In this study, system performance is measured by both the positioning accuracy and location data update frequency. The performance of the GPS/INS Integrated System is compared with that of the GPS alone in this test.

2. RESEARCH APPROACH

General Test Information

The field test was performed in 2008 with the urban roadway network in the Greater Seattle area. Three study routes were chosen for data collection. The first route, as shown in Fig. 1, is a closed loop of about 34 km comprised of freeway sections of I-5, SR520, I-405, and I-90. This route was selected because it goes through downtown Seattle and downtown Bellevue, and contains typical kinds of freeway canopies, including tunnels, overpasses, and bridges. Fig. 2 shows Routes 2 and 3, which were selected to analyze the effects of road surface altitudes and high-rise buildings, respectively. They are comprised of local streets in downtown Seattle. Route 2 is completely located in an urban canyon area with the road surface elevation increasing significantly from southwest to northeast. This route can be used to evaluate the impact of road surface elevation on positioning accuracy. Route 3 traverses both an urban canyon area and a non-canyon area. In a non-canyon area, there are fewer tall buildings than in an urban canyon area. Data from Route 3 were used to show the performance difference between working in an urban canyon area and an urban non-canyon area.

The GPS equipment used in the field test was a Pro XR manufactured by the Trimble Navigation Limited. The Pro XR is a 12-channel, real-time DGPS receiver working on single frequency. The GPS/INS Integrated System tested was a POS/LS from the Applanix Corporation. The equipment was chosen based on criteria of both popularity and availability. These two sets of devices were put into a probe vehicle for the field test. The antennae for the two systems were closely fixed on the roof of the test vehicle above the POS/LS.

FIG. 1 Test Route 1.

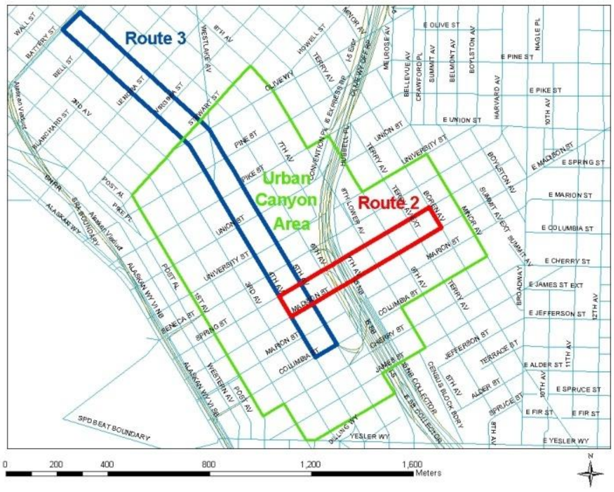

FIG. 2 Test Route 2 and Route 3.

Equipment Settings

In the field test, the Pro XR was customized for the navigation task. In the navigation task, the accuracy is not as high as that in the survey task, but the data update frequency is more consistent. Some preliminary tests were performed to find out the most suitable settings for the navigation task. The Position Dilution of Precision (PDOP) mask was set to 7.0 in the test, which was a fairly high value. The Pro XR would disregard the position data when the PDOP value was higher than the threshold of 7.0. With a higher PDOP mask, the Pro XR can calculate its position even though the satellites' configuration is not positioned well in the sky. However, the positioning accuracy of the GPS was decreased in such cases. The Signal-to-Noise Ratio (SNR) mask was set to 3.5, which was a low value. SNR indicates the signal strength received by the Pro XR from a satellite. The Pro XR would disregard the signal from a satellite when the SNR value for this satellite was lower than the threshold of 3.5. With a lower SNR mask, the Pro XR can still use a signal from a satellite even though the received signal from the satellite is poor; however, the positioning accuracy of GPS decreases because of the lower SNR mask. The Elevation mask was set to 14º, which was a low value. The Pro XR would disregard the signal from a satellite when the elevation of this satellite above the horizon was lower than the threshold of 14º. The real-time-differential mode was set to auto. In this mode, the Pro XR automatically applies real-time differential correction and logs the DGPS data if it can receive correction signals from base stations; when no correction signals are received, the Pro XR will log the GPS data rather than apply the real-time differential correction.

The position mode was set to "Manual 3D" for some runs and "Automatic 3D/2D" for others. These two modes are those most frequently used for tracking vehicles in urban areas. In "Manual 3D" mode, the Pro XR always needs at least four satellites to compute any 3D GPS position. If there are less than four satellites available, the Pro XR does not log any GPS position. In the "Automatic 3D/2D" mode, the Pro XR can compute a 3D GPS position if there are at least four available satellites; when there are only three satellites available, the Pro XR can still compute a 3D GPS position by assuming that the receiver altitude remains the same as the last GPS position. The Real-Time Kinematic (RTK) mode was set to "ON," which means the Pro XR applied RTK in the test if the signals from RTK stations were received. The interval of logged points was set to one second. The measurement unit was feet, and the antenna height was 1.83 m (6.0 feet). The coordinate system was NAD83, Washington State North Zone State Plane.

In the urban area, the POS/LS used both the GPS and INS components to track the test vehicle. The GPS chipset in the POS/LS applied RTK in the test. Before being used for navigation, the POS/LS needs a Rapid Initialization Procedure (RIP) to align to geographic north and the level plane. With RTK GPS, the POS/LS RIP does not have to be performed at a known point; instead, it can be performed at any place with no canopy. During the test, the POS/LS did not require stops for Zero Velocity Updates (ZUPTS) to limit error propagation because of the integrated GPS receiver. The logged points interval of POS/LS was set to one second (or 1 Hz data update frequency) for this test, although the data update frequency can be set to as high as 200 Hz.

Test Procedure

The field test was comprised of two parts: a morning period and an afternoon period. Before each period, approximately 20 minutes was spent to perform the RIP for the POS/LS in the E12 parking lot at the University of Washington. The E12 parking lot was chosen for the RIP was due to its large open space which guaranteed the availability of satellite signals that were essential for the process.

The morning test started at 9:35 A.M. and ended at 11:42 A.M. The test vehicle ran four times along Route 1. The test time for each run ranged from 22 to 25 minutes. Traffic flow on Route 1 was light, and no incident occurred during our test period. Consequently, the test vehicle could repeatedly run along the test loop with a fairly constant speed.

The afternoon test started at about 1:05 P.M. Route 3 was tested first, with the starting point at the intersection of Steward Street and 5th Avenue. Twelve runs were conducted on this route. The position mode was set to "Manual 3D" for the first eight runs, then to "Automatic 3D/2D" for the last four runs. Traffic volume on Route 3 was heavy. Because of the congestion and delays at signalized intersections, the travel time for each run ranged from 11 minutes to 23 minutes. Consequently, a large data sample was collected for Route 3. The test on Route 2 began immediately after the test on Route 3 was completed at 4:44 P.M. The starting point for Route 2 was the intersection of Columbia Street and 5th Avenue. Eight runs were conducted along this route. The position mode was set alternately between odd numbered and even numbered runs, i.e., the position mode was set to "Manual 3D" for the first, third, fifth, and seventh runs, and to "Automatic 3D/2D" for the second, fourth, sixth, and eighth runs. The traffic condition on Route 2 was better than that on Route 3, but was still congested. Each run along Route 2 took approximately 9 minutes.

3. ANALYSIS AND RESULTS

Data Analysis

All data used for this analysis were logged in real time by the POS/LS and the Pro XR. We used both the positioning error and the data update interval to measure the performance of the POS/LS and the Pro XR for vehicle tracking. To analyze the positioning accuracy of the devices, the error of each logged position had to be calculated. Since the exact location of the test vehicle at a particular time was unknown, calculating the exact position error was difficult. However, by breaking the tracking error down into across-track error and along-track error, we could easily calculate the across-track error, which was of our interest for vehicle positioning. The across-track error was defined as the perpendicular distance from a GPS or GPS/INS Integrated System observed position to the corresponding street along which the test vehicle was traveling. The along-track error was defined as the distance from the projected point to the real position of the vehicle on the street.

Fig. 3 illustrates the definitions of across-track error and along-track error. At turning corners, a logged position may correspond to a true vehicle position on either of the roads. In such cases, the across-track error for each condition was calculated and the smaller one was chosen. According to Melgard [3], the across-track error and the along-track error should be of the same order of magnitude. Therefore, the across-track error can be used to represent the true tracking error at each logged point. However, the across-track error is always smaller than or equal to the true tracking error, and the evaluated positioning error in this study should be considered conservative.

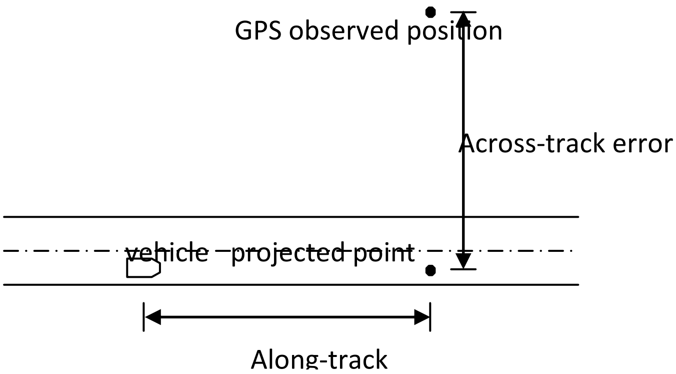

FIG. 3 Across-track Error and Along-track Error.

The across-track errors were calculated from both the logged position data and the street position data from the GIS. The geographic information for the roadways in the test area was obtained from the Washington State Geospatial Data Archive in the University of Washington Libraries. The coverage files were provided by the King County Street Network (KCSN). ArcGIS™ System was used to display the roadway maps.

Test Results and Discussion

Positioning Accuracy

All the calculated errors in this study are indeed across-track errors. For the purposes of this discussion, "error" is used to refer to "across track errors."

Trajectories of the test vehicle logged by the POS/LS and the Pro XR were plotted on GIS maps of the highway and street networks with aerial photographic backgrounds. Fig. 4 shows a typical part of the vehicle trajectory logged by the Pro XR on the freeway segments that were part of Route 1, with the trajectories of the four independent runs shown in red. This figure shows that most of the GPS tracking results on the freeway route were quite accurate because the four runs overlapped well for most of Route 1. Although the tracking errors increased when the test vehicle was traveling under bridges, the logged vehicle positions were still within the reasonable range, as can be seen in Fig. 4. The reason for this might be that the test vehicle was in the signal-blocked area for only a very short period. Since the test vehicle was traveling at about 100 km/h and the bridge was not very wide, GPS satellite signals could be quickly re-obtained after the test vehicle passed the bridge. However, if the test vehicle had traveled in a long tunnel, GPS signals would have been totally lost for a long time and the positioning error would have been much higher. In the test on freeways, the longest location update interval, 38 seconds, was observed when the test vehicle was in a tunnel on I-90. The largest position error on Route 1, 154 m, was also observed when the test vehicle was in the same tunnel. The positioning accuracy of the POS/LS, whether it was under canopy or not, was consistently better than that of the Pro XR. All the POS/LS recorded vehicle positions were within the boundary of Route 1. The largest position error of the POS/LS was about 5.5 meters, much smaller than that of the Pro XR. The position data update frequency of the POS/LS was consistently 1 Hz.

FIG. 4 Part of the GPS Result on Freeway.

Fig. 5 shows the Pro XR-produced tracking results for Routes 2 and 3 in downtown Seattle, most of which were in an "urban canyon" area. The accuracy and precision of the GPS-produced tracking results for these downtown streets were much worse than those for freeways. Fig. 6 shows the tracking results for the same routes produced by the POS/LS in downtown Seattle. We can easily see that the positioning accuracy between the Integrated System and the GPS alone was very different. Hence, our analysis will focus on the performance differences between the two systems for tracking vehicles on downtown streets (Route 2 and Route 3).

FIG. 5 GPS Results in the Urban Area.

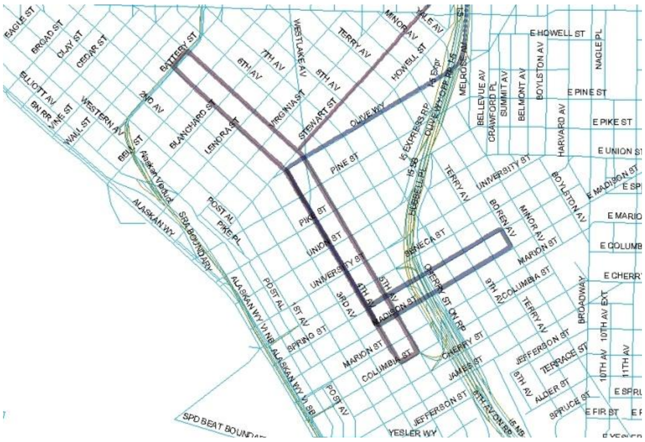

FIG. 6 Integrated System Results in the Urban Area

Table 1 shows the descriptive statistics and t-test results for the GPS errors based on the Pro XR logged position data for Routes 2 and 3. The road surface elevation changes more drastically on Route 2 than on Route 3. The average slope rate of Route 2 is approximately 10.6:1, and that of Route 3 is approximately 42.8:1. Since GPS receivers in the 2D mode assume position elevation is constant when calculating its new position coordinates, the elevation difference along Route 2 should decrease the positioning accuracy of the Pro XR. However, the mean position error of the Pro XR in 3D/2D mode for Route 2 was 6.89m, which was much lower than that of 30.00m for Route 3 in the urban canyon area. This result implies that the effect of road surface elevation on GPS position error may not be dominant in certain urban environments. For this particular case, the lower error for Route 2 is probably due to the lower density of high-rise buildings along it. During our test runs along Route 2, the signal availability was good and about 60% of positioning calculations were done in the 3D mode even though the Pro XR was set to automatic 3D/2D mode. This indicates that the constant elevation assumption required for positioning calculation in the 2D mode was not frequently used. Hence the error, possibly caused by the drastic elevation change along Route 2, was largely avoided.

TABLE 1 DESCRIPTIVE STATISTICS AND T-TEST RESULTS FOR GPS ERRORS IN DOWNTOWN AREA

Route	Area	Position mode	Total GPS observed position	Error (m)				t-ratio (significant level: p)
				Mean	Standard deviation	Max	Min	
Route 2	Urban canyon	3D	511	4.36	4.48	41.76	0.04	-4.861 (0.000)
		3D/2D	821	6.89	13.74	247.42	0.00	
Route 3	Urban canyon	3D	850	14.51	20.43	178.06	0.01	-7.015 (0.000)
		3D/2D	495	30.00	46.56	663.09	0.01	
	Urban non-canyon	3D	1324	4.27	4.06	43.94	0.01	-5.077 (0.000)
		3D/2D	545	6.14	8.21	66.61	0.02	

For each given route, the positioning accuracies of the Pro XR were significantly different between the 3D mode and the 3D/2D mode. For Route 2, the mean error for the 3D mode was 4.36 m which was significantly lower than the mean error of 6.89 m for the 3D/2D mode at the p=0.01 significance level. Separate t-tests were conducted to compare the positioning accuracy between the 3D mode and the 3D/2D mode for urban canyon and urban non-canyon areas. For both areas, the t-ratios indicate that the mean errors for positions produced under 3D mode were consistently lower than those under 3D/2D mode, and the results were significant at p=0.01 significance level.

With test data from both Route 2 and Route 3, positioning accuracies of the Pro XR in the urban canyon area and the urban non-canyon area were also compared using the t-test. The t-tests show that the Pro XR accuracy was significantly higher for the urban non-canyon areas than for the urban canyon areas. The t-ratios were 14.435 (p=0.000) for the 3D mode and 11.239 (p=0.000) for the 3D/2D mode. Urban canopies such as high-rise buildings seriously affect the performance of GPS because they reduce the visibility of GPS satellites. Additionally, high-rise buildings tend to cause the multi-path effect which will result in unpredicted positioning errors. This indicates that sufficient attention should be given to GPS positioning accuracy when used in urban canyon areas.

Table 2 shows the descriptive statistics and t-test results for the GPS/INS Integrated System errors. The calculation was based on the POS/LS logged position data for Routes 2 and 3. The performances of the POS/LS were much more consistent and significantly better than those of the Pro XR, regardless of the road surface slope and high-rise building density. Based on data collected from both urban canyon and urban non-canyon areas, the mean error of the POS/LS was 4.23 m, and the standard deviation was 3.44 m. This indicates that the POS/LS provided much higher positioning accuracy in the test than the Pro XR.

TABLE 2 DESCRIPTIVE STATISTICS AND T-TEST RESULTS FOR THE INTEGRATED SYSTEM ERRORS IN DOWNTOWN AREA

Area	Total Integrated System observed position	Error (m)				t-ratio (significant level: p)
		Mean	Standard deviation	Max	Min	
Urban canyon	12355	4.22	3.48	14.47	0.001	0.633 (0.527)
Urban non-canyon	2844	4.27	3.22	12.79	0.001	
Both areas	15199	4.23	3.44	14.47	0.001	

Position Data Update Frequency

Besides the positioning accuracy, the position data update frequency is also very important for real-time vehicle tracking. Since a GPS receiver cannot update its location without sufficient satellite signals, the actual position data update frequency may be much lower than the setup value when applied under canopies. Suppose an information sign at a downtown bus stop should show bus positions in real-time. If there is no bus position update for 5 minutes, and finally there is an update but the bus is misplaced hundreds of meters away, no passenger will trust the system. Therefore, we also regarded the position data update frequency as an important measure of tracking system performance in our study. Considering that it is difficult to measure the actual update frequency for position data, we chose to use the number of long update intervals for position data to reflect the systems' capability in this aspect. Long update intervals were defined as those intervals longer than one minute for two consecutive position updates. The position data update frequency for the Pro XR was set to 1 Hz, but a significant number of long update intervals were observed in our field test, especially in urban canyon areas. Table 3 shows the observed number of long position update intervals with the Pro XR during our tests on Routes 2 and 3.

TABLE 3 LONG GPS-LOCATION-UPDATE INTERVALS IN DOWNTOWN AREAS

Route	Area	Position mode	Total travel time (Min)	Number of observed long update intervals				
				1~2 (min)	2~3 (min)	3~4 (min)	>4 (min)	Total
Route 2	Urban canyon	3D	22.72	4	2	0	0	6
		3D/2D	24.72	2	0	0	0	2
Route 3	Urban canyon	3D	64.75	15	2	2	1	20
		3D/2D	24.38	7	0	1	0	8
	Urban non-canyon	3D	28.07	1	0	1	0	2
		3D/2D	10.30	0	0	0	0	0

As previously mentioned, satellite signal availability is poor in urban canyons because of the blocking effect of high-rise buildings. Thus, the GPS location update intervals in urban canyons should be longer than those in urban non-canyons. This was supported by our test data from Route 3. Route 3 was comprised of streets in both urban canyon and urban non-canyon areas. The test vehicle spent about two thirds of its travel time in urban canyon area and the rest in urban non-canyon area on Route 3. When the Pro XR was in the 3D mode, 20 long intervals were observed in the urban canyon area, versus two such intervals in the urban non-canyon area. The difference of observed long update intervals between the two areas, eight in the urban canyon area versus zero in the urban non-canyon area, was also significant when the Pro XR was running under 3D/2D mode. The chance of observing long update intervals in urban canyon areas was proven to be much higher than that in urban non-canyon areas.

Since the 3D/2D mode reduces the required number of visible satellites from four to three, the Pro XR should have fewer long-update intervals when in 3D/2D mode than in the 3D mode. In the test on Route 2, we observed 6 long –update intervals when the Pro XR was under the 3D mode, much more than the 2 long-update intervals under the 3D/2D mode. The mode impact on position update frequency was also verified by the test on Route 3: 22 long update intervals under the 3D mode versus 8 under the 3D/2D mode. This indicates that, by setting a GPS alone device in 3D/2D model, a better position data update rate can be achieved.

Unlike the GPS alone device, whose position data update depends always on satellite signal availability, the POS/LS can maintain a constant frequency for position date update because the INS takes the role of the GPS for positioning when satellite signal availability is poor and the INS does not rely on external inputs. Throughout the test, we observed that the POS/LS consistently provided position updates at 1 Hz as planned. If necessary, the location data update frequency of the POS/LS can be set even higher as the system support position data update up to 200 Hz.

4. CONCLUSIONS

Vehicle tracking has become an increasingly important issue in recent years. GPS is naturally considered a reasonable solution for tracking vehicles. Since GPS is known to have problems when working under canopies, questions have been raised on the accuracy of using GPS alone for vehicle tracking in urban areas and whether more reliable tracking solutions have been available. To answer these questions, we conducted a field test to collect the performance data of a GPS (Pro XR) and a GPS/INS Integrated System (POS/LS) for tracking vehicles and compared the performances between the two systems. Unlike most existing evaluation studies that considered only positioning accuracy, position data update frequency was also taken into account.

Our analysis results indicated that while GPS alone was reasonably accurate for tracking vehicles on freeways, it had noticeable problems, in both positioning accuracy and data update reliability, when used on streets in urban canyon areas. On the other hand, the GPS/INS Integrated System performed consistently well regardless of the test areas and roadway types.

To evaluate the positioning accuracy, the observed position data were plotted in GIS maps and across-track errors were calculated and analyzed. The positioning accuracy of GPS varies significantly under different canopy levels and working modes. The t-tests showed that the GPS positioning accuracy for urban non-canyon areas was significantly higher than that for urban canyon areas. When working in 3D mode, the GPS device produced significantly more accurate position data than in 3D/2D mode. Its mean across-track error varied from 4.36 m to 30.00 m in the test runs in urban canyon area and from 4.27 m to 6.14 m in urban non-canyon areas. The standard deviation of GPS across-track error varied from 4.06 m to 46.56 m for different modes and locations in urban areas. The GPS/INS Integrated System, on the other hand, worked consistently well whether in urban canyon areas or in urban non-canyon areas. The mean across-track error of the Integrated System varied from 4.22 m to 4.27 m, and the standard deviation varied from 3.22 m to 3.48 m.

Our analysis on the GPS position update frequency found that the number of long update intervals was significantly affected by canopies and working modes. The chance of having long intervals for position updates was higher when the GPS device was set to 3D mode than to 3D/2D mode. Similarly, the GPS device had more long update intervals in urban canyon area than in urban non-canyon area. The data update frequency of the Integrated System was constantly 1 Hz as specified.

According to the quantitative evaluation results, GPS may have two possible problems when tracking vehicles in urban area: vehicle misplacement and delayed position update. The maximum GPS positioning error identified in this study was more than 663 m, which was enough to misplace the vehicle several blocks away. If such misplacement errors occur frequently, users will definitely question the accuracy of the tracking system. Due to the high roadway density in downtown area, frequent vehicle location updates are desired to monitor vehicles effectively. The longest position-data-update interval in our test was more than 4 minutes, which was long enough to question if the system was still working. Although a better data update performance can be achieved by setting the GPS to the 3D/2D mode, the degradation of positioning accuracy may counteract the gain and makes the overall impact on performance unpredictable.

As a new tracking system, the GPS/INS Integrated System did not have the above problems in our test. It surpassed the GPS alone device in both positioning accuracy and data update performance in our test. The mean positioning error of the Integrated System was less than 4.27 m, and the largest positioning error was 14.47 m in urban areas. Even the largest positioning error was still not enough to cause misplacement problems. The position data update frequency of the GPS/INS Integrated System was always 1 HZ in the field test, and the frequency may be set to an even higher level. The accuracy level and data update frequency of the GPS/INS Integrated System makes it capable for most vehicle tracking tasks in urban canyon areas.

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