Performance Evaluation of RTK-GNSS with Existing Sensors in Dense Urban Areas

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Abstract: The increasing demand for navigation and automation has led to the development of a number of accurate and precise navigation applications that make use of the GPS (Global Positioning System) and other sensors. However, GPS tends to suffer from multipath error, especially in urban environments. To overcome this problem, a method was developed for improving RTK-GPS (real-time kinematic GPS) using a low-cost IMU (inertial measurement unit) and conventional vehicle speed sensors. Additionally, RTK-GNSS (Global Navigation Satellite System) was also evaluated to improve the RTK performance using GPS, QZSS (Quasi-Zenith Satellite System) and BeiDou. In this study, it was found that a suitable measurement quality check is required to obtain better direction information. The results of the experiment demonstrate that, to some extent, our proposed method is beneficial as an alternative to the conventional RTK-GPS in an urban environment.

Key words: GNSS, RTK, IMU, Multipath, ITS.

1. Introduction

The GPS (Global Positioning System) technology is expected to be used more extensively in urban areas. The presence of a large number of buildings in such areas causes the occasional reflection or diffraction of satellite signals, resulting in considerably large multipath errors, of the order of several meters, at the receivers. To ensure the reliability of the GPS when it is used, for example, in an ITS (intelligent transportation system), positioning errors need to be minimal and must be restricted to a threshold. Detecting the inferior quality of observation data is also important for enhancing the reliability of the GPS. For the purpose of ITS, a RTK-GPS (real-time kinematic GPS) has been evaluated by many researchers as one of the high accurate positioning techniques [1-3].

We have revealed the relationship between the reliability and the quality of GPS observation data in

RTK-GPS. At the recent several conferences, we discussed the limitations of the ratio test and the signal quality test [4, 5]. These previous works demonstrated that the simultaneous use of the ratio test and the signal quality test is quite effective for improving the reliability and availability of the RTK-GPS in dense urban areas. When our previously proposed method was used, the percentage of solutions that were within an absolute horizontal error of 1 m increased to over 95% for dense urban areas; however, the availability of the RTK-GPS fell significantly short of the desired value of 100%. The main objective of the present work was to increase the availability of an RTK-GPS in an urban environment. The specific goal was to achieve 100% availability, with a maximum absolute horizontal error of 1.5 m. The error value of 1.5 m was selected in order to ensure lane recognition, even under the maximum absolute horizontal error condition, in the eventuality that this RTK-GPS was used in an ITS. In order to achieve this goal, we needed to use an IMU (inertial measurement unit) and a vehicle speed sensor. Loosely coupled integration

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was adopted for this evaluation. The integration of the RTK-GPS with other sensors is described in the following text. As a first step in the experiment, the quality of the complete observation data was examined based on the carrier-to-noise ratio and the satellite elevation angle. The main purpose of the first-step examination was to control the degradation in quality caused by NLOS (non-line-of-sight) signals. After the signal quality was examined, the popular LAMBDA (least-squares ambiguity decorrelation adjustment) method and the ratio test were used to obtain position fixes [6, 7]. The ADOP (ambiguity dilution of precision) was also used for ambiguity resolution [8]. When RTK fixed positions were not available, a DGPS (differential GPS) and velocity information based on the Doppler frequency were used to determine the positions via a Kalman filter.

For specific use in an RTK-GPS, we developed the method for detecting incorrect fixes. When a fixed position deviates from the expected range of the position deduced using the IMU and vehicle speed sensors, the position fix is regarded as incorrect. When GPS positions were not available, they were corrected by using the IMU and vehicle speed sensors to determine the positions via a Kalman filter. To achieve high accuracy, the calculation used to determine the direction was selected appropriately, depending on a few cases defined in terms of the vehicle dynamics and satellite geometry.

The experiment described above was performed in a dense urban area in the center of Nagoya, Japan, which has a longest satellite outage of over 100 s. A POSLV (Position and Orientation System for Land Vehicles) was used to estimate the reference positions within a deviation of 10 cm [9]. The availability of dual-frequency RTK-GPS solutions was approximately 30%. Using our proposed method, all the incorrect position fixes of the RTK-GPS with horizontal errors of more than 2 m were detected. The standard deviation of the estimated direction for each

epoch was improved to 0.37° . Furthermore, the standard deviation of the estimated vehicle speed was improved to 0.04 m/s by adopting our proposed method, which uses both the speed sensor and the IMU sensor; a standard deviation of 0.1 m/s was observed when only the speed sensor was used. Finally, using the proposed method, 100% positions were obtained over all epochs and 90% of all absolute horizontal errors were below 1.5 m.

In addition to the above results, RTK-GNSS (Global Navigation Satellite System) was also evaluated in a dense urban area in the center of Tokyo, Japan, to improve the RTK performance using GPS, QZSS (Quasi-Zenith Satellite System) and BeiDou. Since we did not equip the IMU and vehicle speed sensors in this test, only RTK-GNSS performance was summarized in this paper.

2. RTK Algorithm Used in This Study

In this study, the LAMBDA method was used to search for correct ambiguities, because this technique is able to search for the best solution using the integer least-squares method [6]. A ratio test was used to determine whether the ambiguities produced by the LAMBDA method were acceptable. The general threshold for the ratio test was set according to Ref. [7]. The RTK used in this paper was supported by the Doppler frequency information to enhance the float solution. The details of the Doppler support RTK are given in Ref. [10]. The LAMBDA method is known to be sensitive to pseudorange or carrier phase error, especially to bias error, and we propose a simple method for improving RTK performance. To avoid bad quality observation data as far as possible, a signal quality test was proposed. The details of the method are discussed in the following section. In addition to the tasks performed in the method proposed in this paper, ADOP was also used for ambiguity resolution, because it was effective in decreasing the number of incorrect position fixes [8].

2.1 Signal Quality Test Algorithm

Conventional signal quality testing was done using the mask angle, minimum C/N_0 , and tracking status information from a GNSS receiver. Here we proposed a further signal quality testing algorithm. Occasionally, due to blocking of the direct signal, only reflected and/or diffracted signals are received in urban areas. In the case of low reflection loss, the GPS receiver tracks the reflected signal as if it is tracking the line-of-sight signal. In this case, the code-tracking error can easily exceed 10 m and a large positioning error is introduced. Although some multipath mitigation techniques [11-13], which depend on the performance of a correlator, can reduce the multipath errors considerably in cases where the direct signal is dominant over the multipath one, they are unable to cope with cases where the multipath signal is dominant, or the direct signal is heavily diffracted. When the reflection surface is not made of metal, the reflection loss will be at least a few dB and usually over 6 dB (at least half amplitude of the direct path will be lost).

The threshold is set to detect the multipath dominant signal. If the difference in the values of C/N_0 between the reference receiver in the multipath-free environment and the rover one in the multipath environment exceeds the threshold, the satellite should be removed from consideration in the positioning. Elevation dependent C/N_0 is used as a reference in the rover site. The value of C/N_0 as a function of elevation is calculated in advance from the rover receiver and the antenna in the multipath-free environment. Based on our many experimental results, this simple detection method works very well in removing satellite signals contaminated by multipath errors. Furthermore, an experiment for the verification of our proposed method was presented at ENC 2010 by the author [14]. In this presentation, the probability of detecting the contaminated satellite signals correctly was quite high.

Fig. 1 shows the elevation-dependent average C/N_0

in both L1-C/A and L2P(Y) signals. The receiver and antenna used in these tests are manufactured by the Javad Corporation. 24 h raw observation data were used to produce Fig. 1. Based on these statistical raw data, the threshold was set for both the L1-C/A and L2P(Y) signals. If the value of C/N_0 of the satellite is below the threshold, the satellite is not used in the positioning. This algorithm was already proposed by Kubo et al. [15], although those investigators used only single frequency data, namely the L1-C/A signal.

The reason why we used dual frequency data for the signal quality test is that diffraction induces many wrong fixes in the RTK. From our many experimental results, we have realized that diffraction causes a deterioration in the carrier phase of the GNSS signal.

Furthermore, the signal strength of the L2P(Y) signal can easily decrease to the level of the minimum threshold for a PLL (Phase Lock Loop) compared with the L1-C/A signal [16].

2.2 Brief Test Using Our Proposed Method

To evaluate our proposed method in a dense urban area, the raw data were obtained using a car in Tokyo from 5:30 p.m. to 6:10 p.m. on August 10, 2011. The total number of epochs was about 12,000. The receiver and antenna used in these tests are manufactured by Javad Corporation. The reference station was set on the rooftop of our laboratory and 1-Hz raw data were obtained. 5-Hz raw data were obtained in the car. The mask angle was set at 10° and

Fig. 1 Elevation dependent C/N_0 (L1-C/A and L2P(Y)).

the minimum C/N_0 of the L1-C/A signal was set at 30 dBHz. If the HDOP (horizontal dilution of precision) was over 10, the solution was not used. Fig. 2 shows the relationship between the number of fixes and the threshold in the L1-C/A or L2P(Y) signal. In RTK, the solutions that satisfy the ratio test were regarded as fixing solutions. The threshold for the ratio test was set at 3. Furthermore, both L1-C/A and L2P(Y) signals were used simultaneously in our proposed method. The threshold was set from 7 dB to 18 dB relative to the average C/N_0 . In the case of a dual-frequency signal quality test (L1+L2 Check), the threshold for the L1-C/A signal was fixed at 12 dB and the threshold for L2P(Y) signal was changed, as shown in Fig. 2. In Fig. 2, the optimum threshold is 10 dBHz, but the threshold depends on the type of receiver and the radio environment.

The number of fixes without our proposed method was 3,293. For every threshold setting, the performance of the RTK using our proposed method was better than the result without our method. As Fig. 2 clearly shows, the use of the L2P(Y) signal was quite effective in increasing the number of fix. Moreover, the simultaneous signal quality test for both L1-C/A and L2P(Y) signals gave the best performance in this test.

3. Integration of the RTK-GPS, IMU, and Vehicle Sensors

3.1 Coordinate Frame Rotation and Translation

Coordinate frame rotation and translation were considered to be important in this study. The three frames considered were the ECEF (earth-centered earth-fixed) coordinate frame, the body frame, and the NED (north east down) coordinate frame. The origin of the ECEF frame is the center of mass of the earth; the x-axis is toward the 0° latitude (equator) and 0° longitude (Greenwich), the y-axis is toward the 0° latitude (equator) and 90° longitude, the z-axis is parallel to the earth's mean spin axis. The origin of the body frame is the center of the vehicle; the x-axis is

Fig. 2 The number of fix with the range of threshold.

toward the north, the y-axis is toward the east, and the z-axis is parallel to the gravity of the vehicle. Rotation matrices are required to rotate the coordinates between one set and another.

3.2 Speed Estimation

The radio frequency from a GPS has a Doppler shift because of the relative velocity between the receiver and the satellite. It is known that using a carrier frequency is effective in obtaining a precise velocity measurement. The velocity of GPS satellites can be estimated precisely by using the ephemeris information. The velocity of the vehicle can be calculated from the satellite velocity and Doppler measurements according to Ref. [17]. The velocity of the vehicle can be estimated precisely up to several centimeters per second.

The vehicle speed sensor provides a scalar speed measurement. The measurement update rate is usually sufficient for navigation. However, the output is noisy because of the quantized signal. The wheel slip is also a cause of errors. Integration of the vehicle sensor and an accelerometer can improve the speed measurement accuracy.

Fig. 3 shows the speed error of a vehicle sensor only, compared with that of a vehicle sensor with IMU. Table 1 summarizes the mean and standard deviation results for speed error. In this integration system, the velocity of the vehicle was estimated using the velocity deduced from the GPS when the velocity from the GPS was available. When the GPS

Fig. 3 Speed error of vehicle sensor only compared with that of vehicle.

Table 1 Speed error of vehicle sensor.

Speed error (m/s)	Vehicle sensor only	Vehicle sensor + IMU
<i>Mean</i>	-0.068	0.004
<i>STD</i>	0.086	0.039

was not available, the velocity of the vehicle was estimated using both the speed information and the direction during GPS outage. The speed information was derived from the vehicle speed sensor and accelerometer.

3.3 Heading Estimation

A yaw rate gyroscope provides a measurement of the true turning rate with an additive moving bias and a zero mean, i.e., white noise. The true yaw rate and bias can be modeled as follows [18]:

$$\begin{aligned}\dot{\Psi} &= r - b_g - \omega_g \\ \dot{b}_g &= \omega_b\end{aligned}\quad (1)$$

where $\dot{\Psi}$ is the true yaw rate of the vehicle, r is the measured yaw rate, b_g is the yaw rate gyroscope bias, ω_g ($\omega_g \sim N(0, \sigma_g^2)$) is the yaw rate gyro noise, and ω_b ($\omega_b \sim N(0, \sigma_b^2)$) is the noise driving the bias drift. The measurement heading of the RTK-GPS consists of the true heading plus zero mean white noise ($v = N(0, \sigma_v^2)$) if the sideslip is assumed to be zero. The

heading of the RTK-GPS can be modeled as follows [18]:

$$\Psi_{GPS} = \Psi + v \quad (2)$$

The accuracy of the heading obtained only from the GPS depends on the GPS velocity measurements and partly depends on the DOP (dilution of precision). When the speed of the vehicle is lower, the heading from the GPS alone is not reliable because the GPS velocity measurement itself has noise of a few centimeters per second. In addition, the sampling rate of the GPS is less than that of the yaw rate gyro, so when the road curves rapidly, the obtained heading will carry a large error. To obtain a precise position during outage of the GPS, it is very important to remove a heading with large errors. We propose a method to remove a heading with large errors if the moving state of the vehicle is as follows:

- (1) The speed of the vehicle is less than the speed threshold;
- (2) The HDOP is greater than the DOP threshold;
- (3) The yaw rate is greater than the yaw rate threshold;
- (4) The difference between the speeds from the GPS and the vehicle sensor is greater than the threshold;
- (5) The difference between the heading changes from the GPS and the yaw rate gyro is greater than the threshold.

The upper panel of Fig. 4 shows the error of the heading when the velocity can be obtained from the GPS. The reference heading was deduced from POSLV. Large errors can be seen. The lower panel shows the error using our proposed method. Table 2 summarizes the mean and standard deviation results for the heading error. By removing this heading information according to the above moving states, we can get a heading with small errors. Unfortunately, the usable number of headings from the GPS decreases substantially. The yaw rate gyro is used to calculate the heading during the outage of the GPS.

Fig. 4 Heading error from the GPS.

Table 2 Heading error of GPS in the first step.

Heading error (degrees)	Before	After
Mean	-8.30	-0.27
STD	78.46	0.64

A long outage will lead to the heading error becoming large when only the yaw rate gyro is used. To decrease the mean outage of headings obtained from GPS, we considered using the heading with a high yaw rate and high HDOP (5-10). In fact, the threshold for the previous method was 5 in HDOP and 4°/s in yaw rate. An increase in the heading error is thus unavoidable, but in order to limit the error, we divide the situations into four states as follows:

- (1) low HDOP with low yaw rate (below 4°/s);
- (2) high HDOP with low yaw rate (below 4°/s);
- (3) low HDOP with high yaw rate (over 4°/s);
- (4) high HDOP with high yaw rate (over 4°/s).

*low HDOP (below 5), high HDOP (5-10)

In these four situations, the heading from the GPS will also be used and the measurement covariance will

be updated in each state. The measurement equations and covariance are represented as follows:

$$\begin{aligned} z_{\psi} &= \Psi_{GPS} - \Psi_{IMU} \\ R &= \begin{bmatrix} \sigma_{\Psi_{GPS}}^2 & 0 \\ 0 & \sigma_{\Psi_{IMU}}^2 \end{bmatrix} \end{aligned} \quad (3)$$

The heading measurement is bounded from 0 to 2π . Hence, the error must be corrected between the two measurements from the GPS and IMU. As a first step, a heading filter was installed to remove the bounds on the heading from the IMU. When the vehicle is stationary, the heading from the GPS is only noise, so the heading cannot be estimated until the vehicle moves. Thus, as a second step, a filter was installed to avoid this effect during stationary periods. The last accurate heading measurement or estimation from the GPS is fed into the Kalman filter as the measurement, since the GPS measurement is unreliable when the vehicle is stationary. Table 3 summarizes how our proposed method furthermore improves the heading error.

3.4 Position Estimation and Wrong Fix Detection

Although the reliability of the fixed positions was not perfect, the procedure to detect the wrong fix of the RTK-GPS is quite important in this work. During the outage of the RTK-GPS, when we can obtain the velocity from the GPS we use the vertical component of the velocity to calculate the change in altitude. When we cannot obtain the velocity from the GPS, provided we know the slope of the ground, the change in altitude can be calculated from the moving distance of the vehicle as follows. The slope information is estimated using the IMU sensor.

$$\Delta h = \int_{t_1}^{t_2} v \sin(\theta) dt \quad (4)$$

where v is the speed of the vehicle, θ is the slope of the ground deduced from the IMU sensor, and Δh is the altitude change between t_1 and t_2 . Epochs of t_1

Table 3 Heading error of GPS in the second step.

Heading error (degrees)	Before	After
Mean	-0.24	-0.24
STD	0.44	0.37

and t_2 are only used when the RTK-GPS is available. The epoch of t_1 is the last epoch where the RTK-GPS was obtained and the epoch of t_2 is the epoch where the RTK-GPS was restored. Therefore, we can calculate the approximate altitude change between t_1 and t_2 . When the difference between the RTK-GPS altitudes in two epochs is larger than the calculated altitude change as shown in Eq. (4), we can determine that the position in t_2 determined from RTK-GPS represents a discontinuity. The image of the threshold of the height is set as shown in Fig. 5. The red line shows the threshold based on the accuracy of the IMU. This is quite important, because the RTK-GPS position soon after a GPS outage tends to be unreliable. Fig. 6 shows the flowchart of our RTK-GPS/IMU/vehicle sensor integration system.

4. Experiment of RTK-GPS with Multi-sensors

4.1 Results of Experiments

This section presents the experimental results. The experiment was performed in an urban environment in the centre of Nagoya, Japan, in 2010 with the longest satellite outage being over 100 s. A dual-frequency GPS antenna and a high accuracy receiver NovAtel OEM5 were used to obtain the GPS raw data. A MEMS (micro electromechanical system) sensor (Crossbow IMU 440) was used to obtain the accelerometer information and the yaw rate (other MEMS, e.g., Xsens and Epson Toyocom, can ensure the same accuracy in our other experiments), and standard vehicle-loaded wheel speed sensors were used to obtain the speed information (anyone can obtain this information from the vehicle). The sampling rate of this data was 10 Hz and the total data recording period was 1,627 s. The POSLV (Applanix) was used to estimate the reference position in order to recognize the temporal errors deduced from our proposed method.

Fig. 7 shows the horizontal results from our proposed method. The red plots show the epochs that

had a fixed position from RTK-GPS and the blue plots show the epochs deduced from the integration of RTK-GPS with the IMU and the vehicle sensors, or the integration of IMU with the vehicle sensors during GPS outage. The percentage of the fixed position was 32.1% (5,215/16,270) because of the dense urban environment.

Fig. 5 An example of the threshold of altitude.

Fig. 6 Proposed RTK-GPS/IMU/vehicle sensor integration system.

Fig. 7 Horizontal results of the test course.

4.2 Proposed Heading Estimation Result

It is known that the heading given by GPS is highly accurate when the vehicle moves and does not have a high yaw rate. Fig. 8 compares the heading error of the GPS alone (upper panel) with those of the GPS with IMU (lower panel). The true heading was derived from POSLV. Since the data were obtained at 10 Hz, the period of this example was about 74 s. In this test, the threshold of the speed was set at 1 m/s. It is clear that the heading error was smaller for our proposed method compared to the GPS alone. Table 4 summarizes the means and standard deviations of the heading errors in each case.

4.3 Proposed Wrong Fix Detection Result

Fig. 9 shows the example of wrong fix detection. The red plots show the horizontal positions given by RTK-GPS. The green plots show the horizontal positions given by our proposed integration system. It can be seen that there are several wrong fixes in the original RTK-GPS regarding the route of the car. On the other hand, the wrong fixes were detected accurately by our proposed integration method. In this experiment, all of the wrong fixes with an error over 2 m were detected and nearly 70% of those with error between 1 m and 2 m were detected successfully. Table 5 summarizes the results of wrong fix detection.

4.4 Overall Results

Fig. 10 shows the horizontal errors of the original dual-frequency RTK-GPS, and Fig. 11 shows those obtained using our integration method, with both wrong fix detection and new heading estimation. Tables 6 and 7 show the frequency of the absolute horizontal errors obtained using our proposed integration method. It can be clearly seen that our proposed method works very well. Using this method, the maximum horizontal error was below 3.5 m, and the standard deviation was 0.86 m. Horizontal errors were less than 1 m in 82.2% of all epochs, and less than 2 m in over 90%.

Fig. 8 Heading error from RTK-GPS vs. RTK-GPS with IMU.

Table 4 Heading error of GPS vs. GPS with IMU.

Heading error (degrees)	GPS only	GPS with IMU
<i>Mean</i>	-0.27	-0.26
<i>STD</i>	0.64	0.29

Fig. 9 Example of wrong fix detection.

Table 5 Detail of wrong fix detection.

Horizontal error (m)	Number of wrong fix	Number of wrong fix detection
1-2	13	9
2-3	3	3
> 3	259	259

Fig. 10 Horizontal error of the dual-frequency RTK-GPS.

Fig. 11 Horizontal error of the integration system.

Table 6 Horizontal error of the dual-frequency RTK-GPS.

Horizontal error (m)	NUMBER OF EPOCHS	Percentage
< 1m	4,944	30.4
1 m-2m	13	0.1
2m-3m	3	0.0
3m-4m	259	1.6
Outage	11,051	67.9
Mean (m)	0.32	
STD (m)	0.74	

Table 7 Horizontal error of the integration system.

Horizontal error (m)	NUMBER OF EPOCHS	Percentage
< 1	13,379	82.2
1-2	1,296	8.0
2-3	631	3.9
3-4	964	5.9
> 4	0	0.0
Mean	0.65	
STD	0.86	

5. Experiment of RTK-GNSS

This section presents the additional experimental results of RTK-GNSS. Test course is the same test route with the previous test in Nagoya in November 2013. A multi-frequency GNSS antenna and a high accuracy receiver NovAtel OEM6 were used to obtain the GNSS raw data. Since the other sensors were not equipped, only RTK-GNSS performance was evaluated in the dense urban areas using GPS, QZS and BeiDou. The reason why we did not use GLONASS satellites was due to the insufficient performance of the ambiguity resolution developed by us in the challenged environment.

The QZS is considered in the same way as GPS satellites in this paper because the GPS/QZSS ambiguity resolution has already been evaluated, and there is no problem with it [19] and because the QZS timescale is also controlled with respect to the offset from the GPST, similar to the other GPS satellites. Furthermore, the common frequencies and same coordinates are used between GPS and QZS. On the other hand, there are no common frequencies between BeiDou B1/B2/B3 and GPS L1/L2/L5 carrier frequencies. Therefore, the respective reference satellites are selected for the BeiDou and GPS systems when constructing the DD (double-difference) observation equation, in order to retain the integer property of the DD ambiguities. For simultaneous measurements over short baselines (< 10 km), the receiver- and satellite-related errors are completely eliminated, whereas the DD troposphere and ionosphere errors can also be neglected. RTK

algorithm used in this additional test is totally same as the algorithm explained in the previous section. LAMBDA method and Ratio test were used to analyze GNSS data.

The sampling rate of this data was 5 Hz and we collected three consecutive periods in Nagoya. Data recording period in Nagoya was 2,480, 2,288 and 2,566 s. The POSLV was used to estimate the reference position in order to recognize the temporal errors deduced from RTK-GNSS results.

The summary of RTK-GNSS results in Nagoya was shown in Table 8. The first period result was similar to the previous RTK-GPS result mentioned in page 6 because the difference of the fix rate using only GPS was very little. If you look at the improvement of the fix rate by adding QZS and BeiDou to GPS, the performance improvement was clear. When we use GPS/QZS as well as BeiDou satellites, the fix rate was increased to about 50%. Furthermore, horizontal errors were less than 0.5 m in over 99.9% of all epochs in all three periods.

Fig. 12 shows the horizontal RTK-GNSS results from our proposed method with the 56.4% for the

Table 8 RTK-GNSS results in Nagoya (fix rate).

Period	GPS (%)	GPS/QZS (%)	GPS/QZS/BeiDou (%)
#1	32.8	43.6	56.4
#2	18.8	34.5	50.1
#3	23.5	30.4	47.0

Fig. 12 Horizontal RTK-GNSS results of the test course.

period #1. Comparing with the RTK-GPS results shown in Fig. 7 with the fix rate 32.1%, the fix rate was dramatically improved by adding QZS and BeiDou. Furthermore, it clearly shows that the distant coverage in this test course was also improved so much by adding QZS and BeiDou. Distant coverage was quite important indicator for GNSS/IMU integration because IMU requires the shorter period between fixed solutions.

From these results, multi-GNSS will definitely improve the automobile navigation performance using GNSS with sensors. In the near future, we will be able to use Galileo satellites and we can use even GLONASS satellites as long as we can develop the robust RTK software.

6. Conclusions

This paper described an enhanced RTK-GPS with IMU and vehicle sensors for application in an urban environment. In this paper, we proposed the integration of wrong fix detection and heading estimation. Using our proposed method, most of the wrong fixes were correctly detected and the reliability of the RTK-GPS was improved. In addition, our proposed method improved the accuracy of navigation in urban areas. Over the duration of the study, the number of epochs where the horizontal errors were below 1 m increased to 82%, and the availability was improved from 30% to 100%, with a maximum error of 3.5 m.

The additional RTK-GNSS test was conducted to predict the RTK-GNSS performance using not only GPS but QZS and BeiDou. In Asian countries, QZS and most of BeiDou satellites are available. Based on the test results, the fix rate was actually improved so much and sometimes the fix rate with GPS/QZS/BeiDou was more than double with only GPS. That fact will be very important in terms of GNSS/IMU integration.

However, there are still few wrong fixes within several decimeters. Our future work is to reduce the

above wrong fixes and to achieve approximately 50 cm horizontal accuracy of all epochs in an urban environment using multi GNSS satellites as well as other low cost sensors.

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