JPNT 6(1), 17-26 (2017)
https://doi.org/10.11003/JPNT.2017.6.1.17

JPNT Journal of Positioning, Navigation, and Timing

RTK Latency Estimation and Compensation Method for Vehicle Navigation System

Woo-Jin Jang[1], Chansik Park[2†], Min Kim[1], Seokwon Lee[1], Min-Gyou Cho[1]

[1]Department of Control and Robotics Engineering, Chungbuk National University, Cheongju 362-763, Korea
[2]Department of Electronics Engineering/ Research Institute for Computer and Information Communication, Chungbuk National University, Cheongju 362-763, Korea

ABSTRACT

Latency occurs in RTK, where the measured position actually outputs past position when compared to the measured time. This latency has an adverse effect on the navigation accuracy. In the present study, a system that estimates the latency of RTK and compensates the position error induced by the latency was implemented. To estimate the latency, the speed obtained from an odometer and the speed calculated from the position change of RTK were used. The latency was estimated with a modified correlator where the speed from odometer is shifted by a sample until to find best fit with speed from RTK. To compensate the position error induced by the latency, the current position was calculated from the speed and heading of RTK. To evaluate the performance of the implemented method, the data obtained from an actual vehicle was applied to the implemented system. The results of the experiment showed that the latency could be estimated with an error of less than 12 ms. The minimum data acquisition time for the stable estimation of the latency was up to 55 seconds. In addition, when the position was compensated based on the estimated latency, the position error decreased by at least 53.6% compared with that before the compensation.

Keywords: RTK, GPS latency, real-time position, data synchronization, error compensation

1. INTRODUCTION

Recently, autonomous vehicles have drawn much attention in the automobile industry. Among the systems constituting an autonomous vehicle, the navigation system for vehicle navigation is the core system of autonomous driving technology. For the navigation of an autonomous vehicle, accurate position information on the current position and destination is required. The safe driving of a vehicle on the road requires position information with a precision of above lane level. The Global Navigation Satellite System (GNSS) is the most widely used positioning system for a vehicle navigation system. GPS, which is the most widely used GNSS, has a position error of less than 17 m at a 95% probability in the code correlation method of the L1 signal (United States Coast Guard Navigation Center 2008). To overcome the limitation of GPS, a Real Time Kinematics (RTK) system that uses GPS carrier measurement is utilized. RTK generates integer ambiguity and correction value using the satellite signal phase observation value at a base station whose position is accurately known. The generated information is transmitted to rover, and the accurate position of the rover is calculated with a position error of less than several centimeters using a relative positioning technique (No et al. 2012). The disadvantage of RTK is the necessity of a separate base station for relative positioning. Virtual Reference Station (VRS)-RTK is a system that supplemented the disadvantage of existing RTK using the pre-installed base station and the Internet (Inglis 2006).

Satellite navigation systems (e.g., GPS) have a latency problem, where the measured position actually outputs past position when compared to the measured time (Inglis

Received Jan 24, 2017 **Revised** Feb 16, 2017 **Accepted** Feb 20, 2017
†**Corresponding Author**
E-mail: chansp@cbnu.ac.kr
Tel: +82-43-261-3259 Fax: +82-43-268-2386

2006). When there is latency for the position information measured in a vehicle, a position error occurs relative to the actual position, and the position error induced by the latency could significantly threaten the safety of the vehicle. For a general passenger vehicle, a position error of less than 1.5 m is needed to recognize the driving lane, and a position error of less than 0.6 m is needed not to cross the adjacent lane while driving on a road.

For the reason mentioned above, studies on the estimation of latency have been conducted. In an existing study, Inglis compared the position errors of VRS by installing a bar code on the driving path and comparing the time of the bar code recognized in a moving vehicle and the measurement of RTK (Inglis 2006). As a method for compensating the latency of satellite navigation, a method, which compares the positions predicted from the pre-acquired map information and the motion of GPS measurement, was researched (Kim et al. 2016). A method that estimates and compensates latency in combination with an inertial sensor was also investigated (Li & Yao 2014). In the existing research, additional facilities needed to be installed on the driving path or the vehicle, or the information on the driving path was necessary.

In the present study, a system for the latency estimation and compensation of RTK was implemented. To estimate the latency of the RTK system, the speeds from vehicle odometer information and the position change of RTK were compared, and the latency of RTK was estimated from the difference between the two speeds. The current position was calculated from the estimated latency and the change of the RTK position. Fig. 1 shows the flowchart of the RTK latency estimation and compensation method.

In general, the output rate of RTK measurement is lower than that of an odometer. In the case of a GNSS receiver, the navigation results are outputted at a rate of 1~20 Hz, but in the case of vehicle information, the vehicle status can be outputted at a rate of more than 100 Hz (NovAtel 2014). To synchronize the two measurements with different output periods, the values between the RTK speed measurements were estimated using a linear interpolation method. To examine the difference between the two measurements, the measurement of the odometer was delayed by one sample, respectively, and the speed error relative to the RTK velocity measurement was checked. In this regard, the moment showing the smallest speed error was assumed to be the latency of RTK.

To compensate the position error induced by the estimated latency, the change of the RTK measurement was used. The position at the current time was calculated by applying the estimated latency and the speed and moving direction calculated from the current and previous measurements, to the equation of motion.

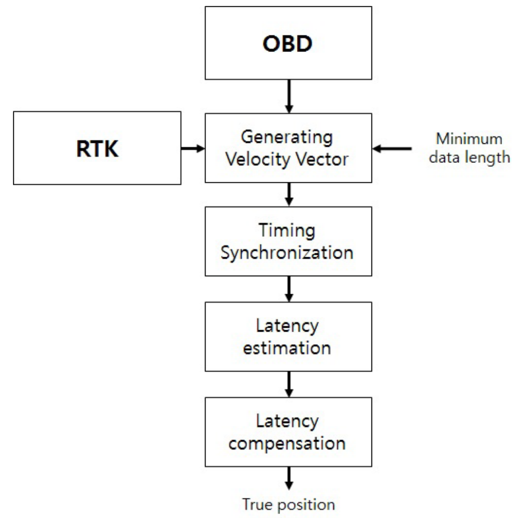

Fig. 1. RTK latency estimation and compensation method.

To evaluate the performance of the proposed method, the data measured from an actual vehicle was applied to the implemented latency estimation and compensation method, and the difference from the actual position was compared.

This paper consists of five sections. In Section 2, RTK and VRS-RTK are explained along with the requirements of a vehicle navigation system. In Section 3, a method for the estimation and compensation of RTK latency is explained. Section 4 describes the experiment for the evaluation of the proposed method and the results of the experiment. The conclusions of this paper are included in the last section.

2. VEHICLE NAVIGATION SYSTEM

2.1 RTK & VRS

The positioning systems, which have a higher accuracy compared with the positioning result of the generally used GPS L1 band code, include the relative positioning methods such as DGPS and RTK (Feng & Wang 2008). For the relative positioning method based on a differencing technique, the error correction information of a satellite signal is calculated at a base station whose position is accurately known, and this value is transmitted to rover. Using the correction information transmitted from the base station, the rover corrects the position error. Among the relative positioning methods, RTK can calculate position information with a precision of several centimeters using the carrier phase observation value measured at the base station. As for the RTK positioning process, the integer

https://doi.org/10.11003/JPNT.2017.6.1.17

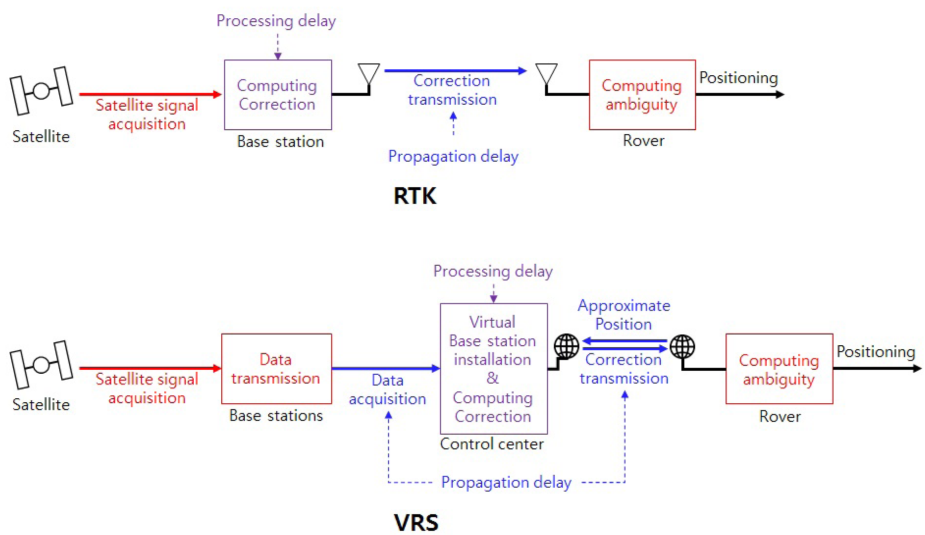

Fig. 2. Positioning method and latency source of RTK and VRS.

ambiguity and correction information are first calculated at the base station, and they are transmitted to the rover. The rover determines the carrier integer ambiguity using the received correction information, and then calculates the position of the rover. RTK performs positioning based on the information of a base station, and thus, a base station whose position is accurately known should be installed near the rover (Rizos 2002).

To supplement the disadvantage of RTK, Network-RTK (VRS), which uses the pre-installed base station and the Internet, is utilized (No et al. 2012). In the case of VRS, the approximate position of the rover is transmitted to the control center using the Internet. The control center obtains the data of the permanent stations adjacent to the rover, calculates the error due to atmospheric effects (e.g., tropospheric error and ionospheric error), and generates a virtual base point near the rover. The position and correction information of the generated virtual base station are transmitted to the rover using the Internet. The rover determines the carrier integer ambiguity using the correction information received from the control center, and then calculates the position of the rover.

Fig. 2 shows the positioning processes of RTK and VRS and the source of relevant latency. Latency occurs in RTK, where the past position is outputted in the positioning process. Latency can be divided into two types: processing delay due to computing time and propagation delay due to data transmission (Langley 1998). The processing delay is the latency occurring at the processing devices that perform the calculation of correction information at the base station and the calculation for integer ambiguity determination at the rover. The propagation delay occurs due to the time for the transmission of correction information from the base station to the rover. In the case of VRS, the information goes through the control center. Accordingly, it also includes the processing delay where the control center obtains the data of permanent stations and installs a virtual base station based on the calculated correction information, and the propagation delay where the approximate position is transmitted from the rover to the control center and the correction information is transmitted to the rover. For VRS, the propagation delay differs depending on the Internet communication environment.

2.2 Vehicle Navigation System

Fig. 3 shows the road environment for vehicle driving. The direction in which a vehicle can proceed (e.g., U-turn and right turn) differs depending on the driving lane. For a vehicle to proceed in the desired direction in a roundabout, the vehicle should drive on the correct lane. In Korea, the minimum width of the lane for vehicle driving is 3 m (The National Law Information Center 2016). When a vehicle on the road drives on the center of the lane, the line that separates the lane is 1.5 m away from the center of the vehicle. Thus, to accurately distinguish the lane where the vehicle is currently located among the lanes on the road, the position error of the navigation system should be less than 1.5 m. In general, the overall width of a passenger vehicle is approximately 1.8 m (Hyundai 2017). When a vehicle drives on the center of the lane, the line is about 0.6 m away from the vehicle. Thus, for a vehicle not to cross the adjacent lane during driving, the error should be less than 0.6 m.

When a vehicle drives on a curved road, the vehicle could

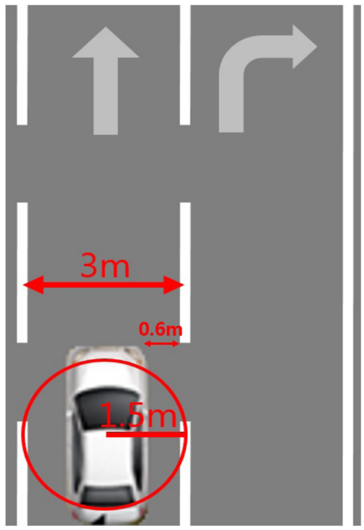

Fig. 3. The direction of lane on the road and required accuracy of vehicle navigation system.

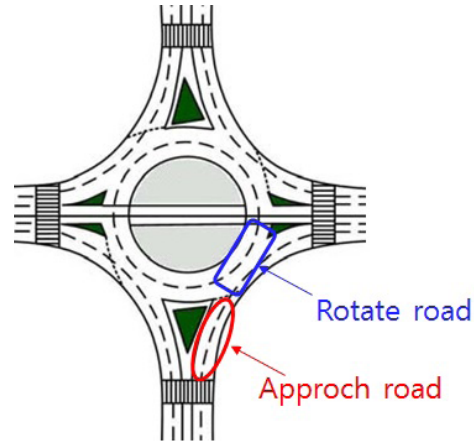

Fig. 4. Structure of round about.

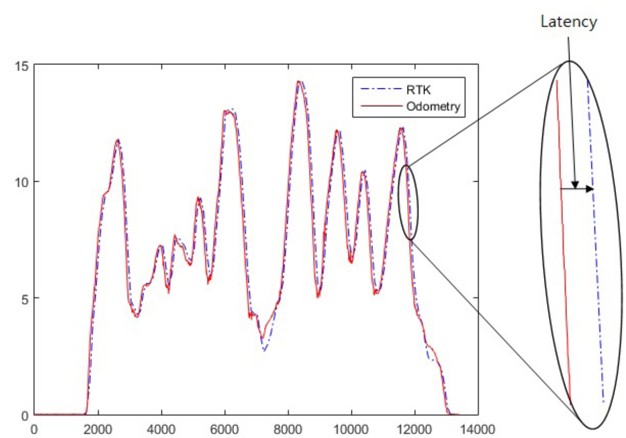

Fig. 5. Velocity vector of wheel speed and delayed RTK speed.

cross the adjacent lane due to latency. Among the roads in Korea, a roundabout is a road environment with the largest curvature (Ministry of Land, Infrastructure and Transport 2014). Fig. 4 shows the structure of a roundabout. The roundabout is divided into an approach road to enter the lane and a rotate road to head for the desired destination.

If there is no change in the speed and direction when entering from the approach road to the rotate road of a roundabout, the vehicle will cross the adjacent lane about 4.5 m ahead. 50 km/h is approximately 14 m/s, and thus the vehicle proceeds 4.5 m after about 320 ms. If the vehicle enters from the approach road to the rotate road of a roundabout with an RTK latency of more than 320 ms, there will be a risk of crossing the adjacent lane. Therefore, the effect of latency for RTK measurement should be smaller than that at a 320 ms latency.

3. LATENCY ESTIMATION AND COMPENSATION

In this section, a method for the estimation of RTK latency and a method for the compensation of the position error induced by latency are described. To examine the latency of the RTK system for the vehicle navigation system, the vehicle wheel velocity and the speed calculated from the position change of RTK were compared. For a vehicle, the speed of the vehicle can be measured from the measurement of the encoder installed at the wheel. In addition, the speed of the vehicle can be calculated from the change of the RTK position measurement. When there is latency in RTK, the RTK latency can be figured out by comparing the change of the two speeds.

Fig. 5 shows the difference in the two vectors due to the latency. By estimating the latency through the comparison of the two vectors, the position error induced by the latency needs to be compensated. To compensate the position error induced by the latency, the speed and vehicle driving direction calculated from the change of the RTK position were used. In the case of the navigation coordinate system for expressing the vehicle motion, the NED coordinate system was used.

3.1 Latency Estimation Method

To examine the latency of the RTK system for the vehicle navigation system, the vehicle wheel velocity and the velocity calculated from the position change of RTK were compared. For a vehicle, the speed of each wheel can be measured from the measurement of the encoder installed at the wheel. The speed of the vehicle can be calculated by averaging the measured speeds of the four wheels. In addition, the speed of the vehicle can be calculated from the position change of RTK during the sampling period.

$$V_{ODO}(i)=\frac{V_{FL}(i)+V_{FR}(i)+V_{RL}(i)+V_{RR}(i)}{4} \quad (1)$$

$$V_{RTK}(j)=\frac{P(j)-P(j-1)}{\Delta t_{RTK}} \quad (2)$$

In Eq. (1), V_{FL}, V_{FR}, V_{RL}, V_{RR} are the speeds for the left front wheel, right front wheel, left rear wheel, and right rear wheel, respectively, and $V_{ODO}(i)$ is the most recent vehicle speed measured by the odometer. In Eq. (2), P is the position, and $V_{RTK}(j)$ is the sampling period of RTK. Δt_{RTK} is the speed calculated using the most recent position change of RTK.

To obtain precise latency, a vector that stored the speed during $t_{\min}$, which is the minimum time for the accurate estimation of RTK latency, was generated.

$$V_{ODO}=\left[V_{ODO}(i)\quad V_{ODO}(i-1)\quad \cdots \quad V_{ODO}(i-\frac{t_{\min}}{\Delta t_{ODO}})\right] \quad (3)$$

$$V_{RTK}=\left[V_{RTK}(j)\quad V_{RTK}(j-1)\quad \cdots \quad V_{RTK}(j-\frac{t_{\min}}{\Delta t_{RTK}})\right] \quad (4)$$

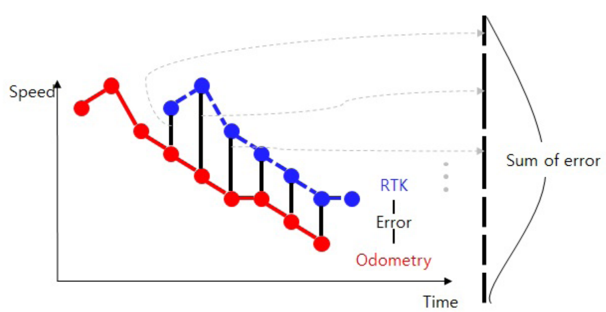

Fig. 6. Error between wheel speed and delayed RTK speed.

In Eq. (3), V_{ODO} is the speed vector that stored the speed measured by the odometer from the time for the most recent measurement until $t_{\min}$ ago. In this regard, Δt_{ODO} is the sampling period of the odometer. In Eq. (4), V_{RTK} is the speed vector using the measurement of RTK. In general, the sampling period of the encoder that measures the vehicle wheel speed is shorter than that of RTK. As the encoder and RTK have different sampling periods, the two vectors, V_{ODO} and V_{RTK}, have different lengths. To compare the two vectors with different lengths, the speed vector V_{RTK}, which synchronized $\bar{V}_{RTK}$ having a longer sampling period with the speed vector of the odometer using linear interpolation, was generated.

$$\bar{V}_{RTK}(i)=\frac{V_{RTK}(m)-V_{RTK}(m-1)}{\Delta t_{RTK}}n+V(m)\,,$$

$$\left(n=1,2,\cdots,\frac{\Delta t_{RTK}}{\Delta t_{ODO}},\quad m=1,2,\cdots,j-1\right) \quad (5)$$

The two synchronized vectors, V_{ODO} and, $\bar{V}_{RTK}$ have the same form, and show a phase difference depending on the latency, as shown in Fig. 5. In this regard, the difference in the two vectors was defined as the speed error, as shown in Fig. 6. If there is latency in the measurement of RTK, the speed error will be the smallest when V_{ODO} is delayed by the latency. To examine the RTK latency of V_{RTK}, the moment showing the smallest speed error between the two vectors was searched by delaying the time axis of V_{ODO} by one sample, respectively.

Fig. 7 shows the speed error vector measured by delaying V_{ODO}. In this regard, V_{RTK} was expressed by a dotted line, and V_{ODO} by a solid line. In the figure, the moment that shows the smallest speed error as the two vectors are matched is the sample that corresponds to the latency.

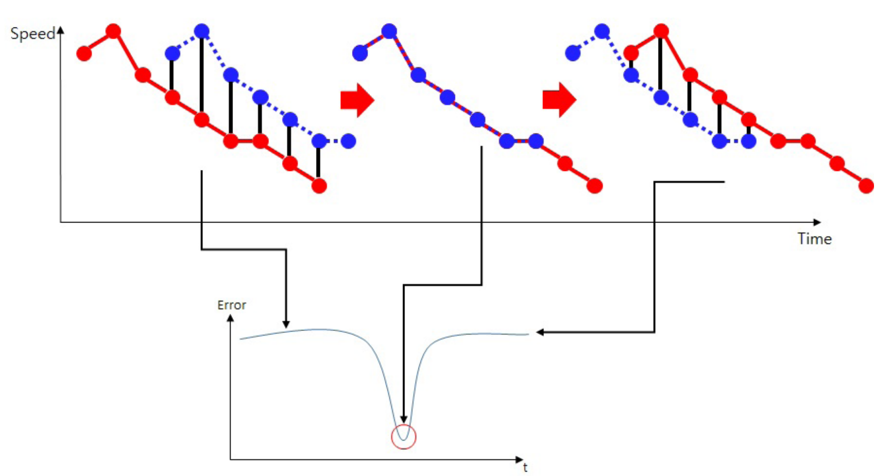

Fig. 7. Error result due to speed vector delay.

$$V_{error}(l) = \sum_{l=1}^{t_m \Delta t_{RTK}} \sum_{m=1}^{i} \left| \overline{V}_{RTK}(m) - V_{ODO}(m-l) \right| \quad (6)$$

In Eq. (6), $V_{error}(k)$ represents the speed error between the two vectors when V_{ODO} is delayed by l sample(s), respectively. The difference between the two vectors is the smallest when the number of delayed samples (l) is delayed by the number of samples corresponding to the latency (L), and in this regard, the latency (δt) can be expressed as the product of the number of delayed samples and the sampling period.

$$\delta t = L \Delta t_{ODO} \quad (7)$$

3.2 Latency Compensation Method

When there is latency in the RTK positioning result, the obtained position is different from the current position. To compensate the position error induced by the latency, the change of the RTK positioning resul t was used. The current vehicle speed and moving direction can be calculated from the position change of RTK measured during the sampling period. When the sampling period is sufficiently short, the change of the speed and moving direction is small, and thus, the position at the current time can be predicted using the current vehicle speed, moving direction and the latency estimated earlier.

The moving direction can be calculated from the change of the positions measured at the previous and current times, as shown in Eq. (8).

$$r(j) = \begin{bmatrix} r_x(j) \\ r_y(j) \\ r_z(j) \end{bmatrix} = \frac{1}{\sqrt{\Delta P_x(j)^2 + \Delta P_y(j)^2 + \Delta P_z(j)^2}} \begin{bmatrix} \Delta P_x(j) \\ \Delta P_y(j) \\ \Delta P_z(j) \end{bmatrix} \quad (8)$$

In Eq. (8), $r(j)$ is the unit vector for the moving direction at time j, and $r_x(j)$, $r_y(j)$, and $r_z(j)$ are the moving direction vector components for each axis. $\Delta P_x(j)$, $\Delta P_y(j)$, and $\Delta P_z(j)$ are the position changes for each axis in the vehicle navigation coordinate system, and they can be calculated based on the difference between the position at time $j[P(j)]$ and the position at time j-1 $[P(j\text{-}1)]$. For the moving direction calculated in Eq. (8), the position error is small when the vehicle is in a straight line motion. However, when the vehicle drives on a curved road, the difference from the actual moving direction increases, and thus position error occurs due to the moving direction. To cope with the curved area, the angular velocity of the moving direction needs to be applied using the information on the past and current moving directions.

$$\Delta r(j) = \frac{1}{\Delta t_{RTK}} \begin{bmatrix} r_x(j) - r_x(j-1) \\ r_y(j) - r_y(j-1) \\ r_z(j) - r_z(j-1) \end{bmatrix} \quad (9)$$

The angular velocity of the moving direction can be calculated as shown in Eq. (9). Δr is the angular velocity that corresponds to the change of the moving direction. Using the moving direction and angular velocity calculated earlier, the current driving direction of the vehicle (h) can be calculated as shown in Eq. (10).

$$h(j) = r(j) + \Delta r(j) \delta t \quad (10)$$

In the case of the method for calculating the vehicle speed from the RTK positioning result, Eq. (2) in the previous section is used. The calculated speed is the past speed by the latency, and it is different from the current speed when the vehicle decelerates or accelerates. To reduce the position error induced by acceleration, the effect of acceleration needs to be included on the calculated vehicle speed. The acceleration can be calculated from the change of the speed per sample based on V_{RTK}.

$$a(j) = \frac{V_{RTK}(j) - V_{RTK}(j-1)}{\Delta t_{RTK}} \quad (11)$$

When the position, velocity, and acceleration of an object are known in the inertial coordinate system, the position after the latency, δt seconds, can be calculated by adding the integral of the speed for δt seconds and the double integral of the acceleration for δt seconds, based on the recent position measurement, as shown in Eq. (12). In this regard, the vector product of the vector for the driving direction(h), the speed and acceleration, which is the movement occurred during δt seconds, is calculated, and it is converted to the change for each axis. In Eq. (12), $\overline{P}(j)$ is the position after the compensation of the position error induced by the latency.

$$\overline{P}(j) = \begin{bmatrix} \overline{P}_x(j) \\ \overline{P}_y(j) \\ \overline{P}_z(j) \end{bmatrix} = \begin{bmatrix} P_x(j) \\ P_y(j) \\ P_z(j) \end{bmatrix} + \left(V_{RTK}(j) \cdot \vec{h}(j) \right) \delta t + \frac{1}{2} \left(a(j) \cdot \vec{h}(j) \right) \delta t^2 \quad (12)$$

4. PERFORMANCE EVALUATION

To evaluate the performance of the implemented latency estimation and compensation method, an experiment was conducted using the data obtained from an actual vehicle. For the vehicle used in the experiment, Hyundai Avante AD was used, and the speed of each wheel was

https://doi.org/10.11003/JPNT.2017.6.1.17

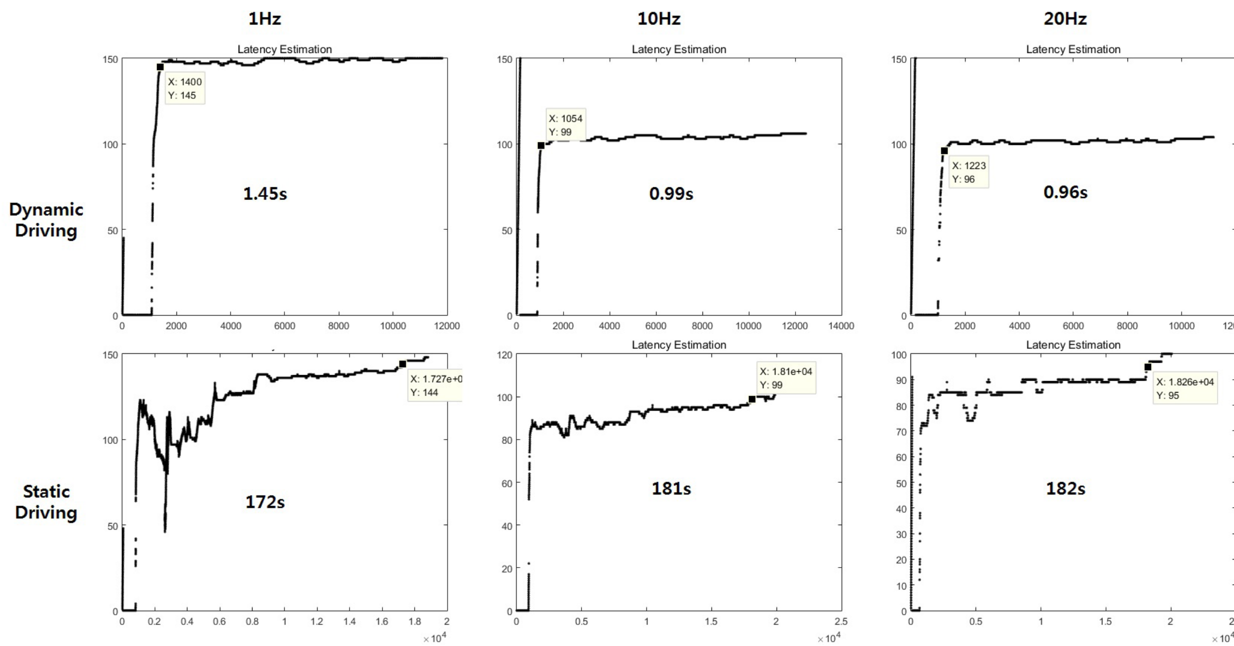

Fig. 8. Minimum driving time to estimate correct latency.

obtained from the On-Board Diagnostics (Hyundai 2017). For RTK, Propak-V3 (NovAtel) was used as the base station receiver, and Flexpak as the rover receiver (NovAtel 2011). The system was implemented using MATLAB in the PC environment. The carrier correction information was transmitted using a PDL4535 RF transmitter/receiver (Pacific Crest 2001). The output rate of the odometer was 100 Hz. Various output rates of RTK were used (20 Hz, 10 Hz, and 1 Hz), and repeated experiments were performed (NovAtel 2010). While driving a total of 1 km (round trip of a 500 m distance) in an RTK available area, the measurements of the odometer and RTK were obtained. For the driving method, constant driving (18~22 km/h) and dynamic driving (10~60 km/h) were used.

First, to examine the performance of latency estimation, arbitrary latency was added, and the latency estimation performance was evaluated. Second, to examine the minimum data acquisition time that can secure the performance of latency (t_{min}), the time required for the convergence of the latency was measured by increasing the length of the signal. Lastly, the position error compensation performance was examined by comparing the actual position and the compensated position using the estimated latency.

4.1 Performance of Latency Estimation

To investigate the performance of latency estimation, the latency estimation performance was examined by adding arbitrary latency to the obtained signal. The RTK measurement was converted so that the obtained data would be delayed by 0 s, 100 ms, 500 ms, and 1 s, and the latency estimation method was then applied. To evaluate the estimation performance, the data for the entire section were used. Table 1 summarizes the latency of the RTK system depending on the output rate when additional latency was not assigned and when arbitrary latency was added. In Table 1, the values in the table represent the latency estimated by the system, and the numbers in parentheses represent the difference between the actual latency and the estimated latency. When additional latency was not assigned, the latencies at each output rate were 492 ms for 1 Hz, 40 ms for 10 Hz, and 20 ms for 20 Hz. Then, the latency estimation performance was examined when 100 ms, 500 ms, and 1 s were additionally delayed. When latency was added to the measurement, the error between the actual latency and the estimated latency was 12 ms for 1 s latency at 20 Hz, which was the largest latency estimation error. The results of the experiment showed that the difference was less than 320 ms in every case.

Table 1. Estimated latency of RTK.

Sampling frequency [Hz]	Mean latency [ms]			
	+0	+100	+500	+1000
1	492	596 (+4)	993 (+1)	1490 (-2)
10	40	140 (0)	540 (0)	1041 (+1)
20	20	113 (-7)	513 (-7)	1008 (-12)

The minimum data acquisition time for securing the estimation performance (t_{min}) was examined by investigating the length of the data necessary for the convergence of the estimated latency to the actual latency. To search the time for the convergence of the estimated latency to the actual latency, the latency was checked by increasing the length of the data by one sample, respectively. The experiment was conducted by assigning an additional latency of 1 s. Fig. 8 shows the results of the experiment. The experiment included dynamic driving, where the speed changed continuously, and static driving, where similar speed was maintained. In the case of the dynamic driving, the times for obtaining a latency estimation error of less than 320 ms were 12.62 seconds for 1 Hz, 9.33 seconds for 10 Hz, and 10.84 seconds for 20 Hz. In the case of the static driving, they were 55.4 seconds for 1 Hz, 9.84 seconds for 10 Hz, and 7.47 seconds for 20 Hz.

For the dynamic driving, the latency could be estimated with an error of less than 320 ms within up to 12.62 seconds, but for the static driving, up to 55.4 second data was needed to estimate the latency with an error of less than 320 ms. In the case of the dynamic driving, the converge was relatively fast, but in the case of the static driving, a longer time was needed for the convergence compared with the dynamic driving.

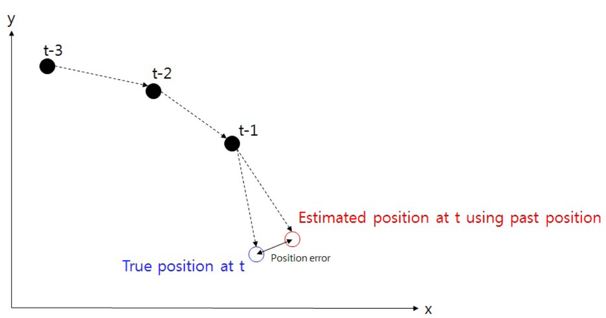

Fig. 9. Experiment method for evaluate position estimation.

4.2 Performance of Latency Compensation

The position error induced by the latency was compensated. To compensate the position error induced by the latency, the compensated position error and the position of the next sample were compared assuming that 1 s was delayed when the output of RTK was 1 Hz, 100 ms was delayed when it was 10 Hz, and 50 ms was delayed when it was 20 Hz. The experiment was performed for the static driving and the dynamic driving. Fig. 9 shows the experiment method, and Fig. 10 shows the results of the experiment.

For the static driving, the status of the vehicle motion did not change significantly, and thus the position error was smaller than that of the dynamic driving. In the case of 1 Hz, the position error for the dynamic driving decreased from 13 m to 1.63 m, and that for the static driving decreased from 5.89 m to 0.9 m. In the case of 10 Hz, the position error for the dynamic driving decreased from 1.44 m to 0.12 m, and that for the static driving decreased from 0.6 m to 0.17 m. In the case of 20 Hz, the position error for the dynamic driving decreased from 0.73 m to 0.16 m, and that for the static

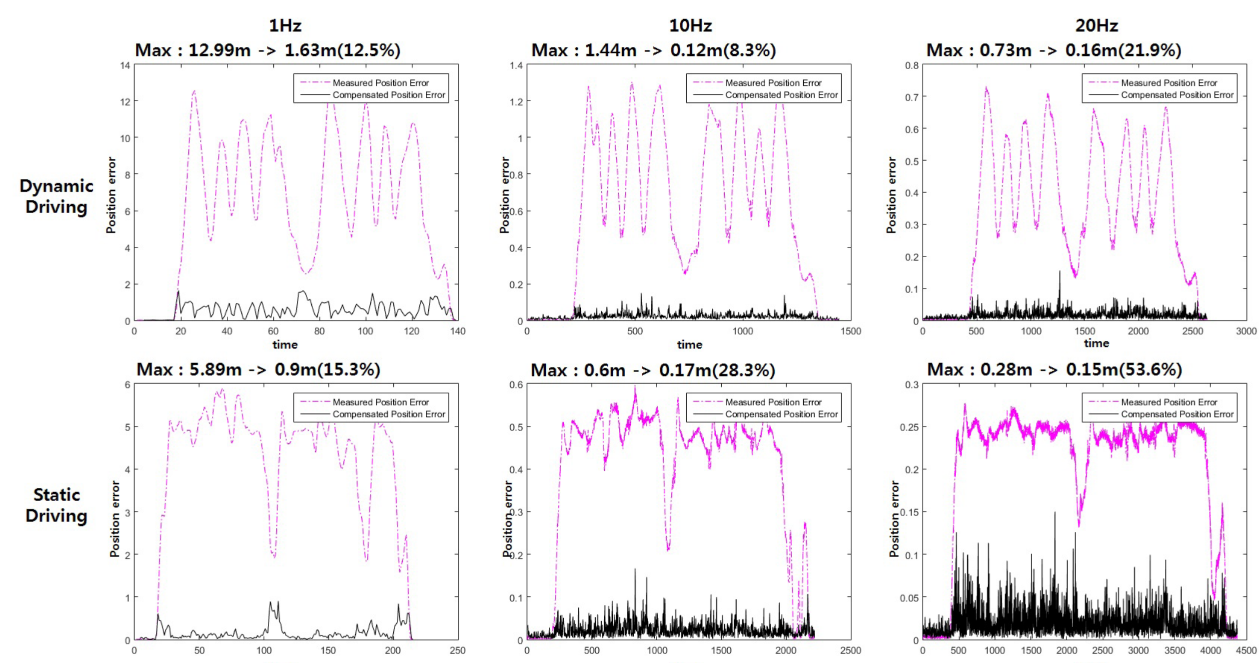

Fig. 10. Maximum error of compensated position.

https://doi.org/10.11003/JPNT.2017.6.1.17

driving decreased from 0.28 m to 0.15 m. All the errors of the compensated positions were less than 0.6 m excluding the case of 1 s latency at 1 Hz. The position error decreased in all the experiments, and the decrease in the navigation error ranged from 53.6% to 8.3%.

5. CONCLUSION

In this study, a method for the estimation and compensation of the RTK latency of a vehicle navigation system was implemented using an actual vehicle, RTK receiver, and the odometer velocity information calculated from the vehicle wheel speed; and the performance of the implemented system was evaluated.

To estimate the latency of RTK, the speed of the vehicle obtained from the RTK positioning result was compared with the speed obtained from the odometer. To compare the speeds of the two systems having different output periods, linear interpolation of the RTK speed was performed so that the output period would be identical to that of the odometer speed. To examine the time difference between the two synchronized speeds, the point showing the smallest speed difference between the two speeds while delaying the odometer speed by 10 ms (i.e., the output period of the measurement), respectively, was assumed to be the latency. Using the estimated latency, the position error was compensated based on the equation of motion. To compensate the position error, the speed, acceleration, and vehicle driving direction were calculated based on the position change of RTK. The position after the estimated latency was calculated based on the calculated speed/acceleration/driving direction and the most recent measurement.

To evaluate the performance of the implemented system, the data obtained from the driving of an actual vehicle were used. When arbitrary latency was added, the added latency could be estimated with an error of less than 12 ms in every case. The examination of the minimum time for latency estimation showed that a maximum of 12.62 seconds was needed for dynamic driving, and a maximum of 55.4 seconds was needed for static driving. Therefore, at least 55.4 seconds of data acquisition time was needed in the experiment environment. Also, it was found that when the system environment changes, the minimum data acquisition time should be searched by examining the latency estimation performance based on static driving at 1 Hz. Lastly, when the position error induced by the latency was compensated, the position errors were less than 0.6 m excluding the case of 1 s latency at 1 Hz. Also, in every case, the accuracy was higher when the position error was compensated.

It is expected that the implemented RTK latency estimation and compensation method can be used for vehicles using RTK, and can also be used for VRS where the latency continuously changes depending on the Internet communication environment.

ACKNOWLEDGMENTS

This work was supported by Institute for Information & communications Technology Promotion (IITP) grant funded by the Korea government (MSIP) (No. R7117-16-0164, Development of wide area driving environment awareness and cooperative driving technology which are based on V2X wireless communication)

REFERENCES

Feng, Y. & Wang, J. 2008, GPS RTK Performance Characteristic and Analysis, Journal of Global Positioning System, 7,1-8

Hyundai 2017, AVANTE [Internet], cited 2017 Jan 20, available from: http://www.hyundai.com/kr/showroom.do?carCd1=RD026

Inglis, R. 2006, Evaluation of VRS-RTK GPS Latency in a Dynamic Environment, Research project Dissertation, University of Southem Queensland, ENG4111/2

Kim, H. J., Lee, W. H., & Yu, K. Y. 2016, Reduction of GPS Latency Using RTK GPS/GNSS Correction and Map Matching in a Car Navigation System, Journal of the Korean Society for Geospatial Information Science, 24, 37-46. http://dx.doi.org/10.7319/kogsis.2016.24.2.037

Langley, R. B. 1998, RTK GPS, GPS World, 9(9), 70-76

Li, B. & Yao, D. 2014, Calculation of Vehicle Real-time Position Overcoming the GPS Positioning Latency with MEMS INS, In Service Operations and Logistics, and Informatics (SOLI), 2014 IEEE International Conference on, pp.248-254. http://dx.doi.org/10.1109/SOLI.2014.6960730

Ministry of Land, Infrastructure and Transport 2014, Round about design guidelines, pp.40, [Internet], cited 2016 Jan 20, available from: http://roaddesign.kict.re.kr/filebank/moctroadguide/CIKCLS126036/CIKCLS126036.pdf

No, S.-J., Han, J.-H., & Kwon, J.-H. 2012, Accuracy Analysis of Network-RTK (VRS) for Real Time Kinematic Positioning, Journal of the Korean society of survey, geodesy, photogrammetry, and cartography, 30, 389-396. http://dx.doi.org/10.7848/ksgpc.2012.30.4.389

NovAtel 2010, OEMV Installation and Operation User

Manual, OM-20000093. http://www.novatel.com/assets/Documents/Manuals/om-20000093.pdf

NovAtel 2011, Propak-V3 and Flexpak USER GUIDE. http://www.novatel.com/assets/Documents/Papers/PropakV3.pdf

NovAtel 2014, OEMStar Receiver Firmware Reference Manual, OM-20000127, pp.191-194. http://www.novatel.com/assets/Documents/Manuals/om-20000127.pdf

Pacific Crest 2001, PDL User's GUIDE, PN: M0052203. http://www.pacificcrest.com/library/Users_Manual_PDL.pdf

Rizos, C. 2002, Network RTK Research and Implementation – A Geodetic Perspective, Journal of Global Positioning Systems, 1, 144-150.

The National Law Information Center, Ministry of Land, Infrastructure and Transport [Internet], cited 2016 Jan 20, available from: http://www.law.go.kr/LSW/lsInfoP.do?lsiSeq=138166#0000

United States Coast Guard Navigation Center 2008, Global Positioning System Standard Positioning Service Signal Specification, pp.34 [Internet], cited 2008 Sept, available from: http://www.gps.gov/technical/ps/2008-SPS-performance-standard.pdf

Woo-Jin Jang received his B.S degree in Department of Electronical Engineering from Chungbuk National University. He is a M.S. candidate in the Department of Control and Robotics Engineering at Chungbuk National University in Korea. His research interests include GNSS Localization, Integrated Navigation System and Attitude Determine.

Chansik Park received his B.S, M.S, and Ph.D. degrees in Electrical Engineering from National University in 1984, 1986 and 1997, respectively. He was a Professor with the School Electronics Engineering, Chungbuk National University, Cheongju, Korea, since 1997. His research interests include GNSS, PNS, SDR, Integer Ambiguity Resolution Algorithm and Error Analysis

Min Kim received B.S degree in Electronics Engineering from Chungbuk National University, Korea in 2016. He is a M.S. candidate in the Department of Control and Robotics Engineering at Chungbuk National University in Korea. His research interests include Software Defined Radio of GPS L2C, GNSS Localization, Integrated Navigation System.

Seokwon Lee received his B.S degree in Department of Electronical Engineering from Chungbuk National University. He is a M.S. candidate in the Department of Control and Robotics Engineering at Chungbuk National University in Korea. His research interests include PNS, PDR, Indoor Navigation System

Min-Gyou Cho received his B.S. degree in Department of Electronic Engineering from Chungbuk National University. He is a M.S. candidate in the Department of Control and Robotics Engineering at Chungbuk National University in Korea. His research interests include multi-constellation Attitude Determine and Heave estimation.