Research Report

Positioning Technique Based on Vehicle Trajectory Using GPS Raw Data and Low-cost IMU

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ABSTRACT This paper proposes a technique of position estimation which is applicable to urban environments where the accuracy of GPS positioning is deteriorating. The method, utilizing GPS Doppler processing and gyros, calculates trajectories by extracting the most reliable azimuth, which is then integrated with vehicle speed. Our approach focuses on integrating these segments of the trajectory with GPS pseudoranges which are received at points throughout the whole trajectory. Using the pseudoranges obtained in the past, it is possible to judge the confidence level of these results. This makes it possible to select the best satellites for positioning. An evaluation test on a road course passing by high-rise buildings and under overpasses in a city area showed that our proposed method achieves more accurate position estimation than conventional methods, demonstrating its effectiveness.

KEYWORDS ITS, GPS, Positioning, Velocity Estimation, Multipath Mitigation

1. Introduction

Recently, various driver assistance systems have been developed. The efficiency of such systems fundamentally depends on precise vehicle localization.(1-3) Vehicle-infrastructure cooperative systems need 5~10 m positioning accuracy for mutual communication.(1) The currently available semi-automatic system that gives warning to the driver (i.e. before a stop sign, intersection, etc.) requires about 1 m accuracy to be effective.(2) Hopefully, in the near future, the automated vehicle control system will require much less distance accuracy for such localization of warnings.

However, the absolute positional accuracy of standard GPS technology right now is a few meters at best. In addition, the positional accuracy level may exceed 30 m in urban areas where multi-path reflections and blocking of GPS signals occur.(4) Therefore, this paper proposes a new technique to achieve 5 m positioning accuracy in city areas.

2. Related Work

Several positioning systems are currently available, e.g. RTK (Real Time Kinematic) -GPS and GPS/IMU (Inertial Measurement Unit). The accuracy of the RTK-GPS is a few centimeters, but it requires several minutes for initialization and continuous communication with a base station. Moreover, it is very expensive and easily affected by signal blocking and multipath conditions that occur in urban canyons.(4) Thus, this technique has not been an ideal option for implementing an accurate and affordable driver assistance system.

The GPS/IMU combination navigation system, which can substitute for the GPS system, has been the positioning system conventionally used in automobiles. This navigation system employs inertial sensors such as gyros and speed sensors. Common GPS/IMU techniques adapt a Kalman Filter or Particle Filter for city area localization.(5-6) However, positioning results and raw data of GPS signals may be affected by large non-systematic errors attributable to multipath. In addition, GPS signal blockages for long periods of time lower the precision of position localization due to accumulated errors in the inertial sensors. It must be kept in mind that the positioning accuracy of such a system largely depends on the high cost inertial sensors.

The standard GPS technology conventionally outputs an absolute position, based on pseudo range. In this paper, we introduce the term GPS raw data, referring to GPS pseudo range and also results of the well known GPS Doppler processing that yields the

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relative velocity between the receiver and a GPS satellite. According to Kojima, et al.,(7) the accuracy of the estimated velocity derived from GPS Doppler processing is better than that using the distances between absolute positions based on pseudo range. Thus, we propose a new method of precise localization utilizing "Bundle Adjustment" of IMU and GPS raw data. This method enables precise localization by optimization of positions all along a route, using GPS pseudo range information and an accurate vehicle trajectory estimated mainly by GPS Doppler processing.

3. Overview of Our Proposal

We propose a new technique of precise localization by Bundle Adjustment of IMU and GPS raw data. **Figure 1** shows the concept of our proposal. **Figure 2** is a schematic explanation of Bundle Adjustment. Our proposal depends on two operations. The first is adjustment of the whole trajectory pathway instead of the vehicle point alone. This method can accommodate signals for positioning from far more satellites than those used for a one-time data input to a GPS receiver. The second is integration of different sets of multipath errors obtained from different locations. These operations can significantly reduce bias errors and subsequently positioning errors.

These two operations, performed using the constellation of satellites, should greatly improve the accuracy of the current positioning system. Then, we estimate vehicle position under the assumption that vehicle trajectory is calculated precisely. Therefore, any errors of vehicle trajectory would affect the positioning result. First, therefore, we introduce a new trajectory estimation technique based on GPS Doppler processing in the next chapter.

4. Trajectory Estimated from GPS Doppler and Inertial Sensors

4. 1 GPS Doppler Processing

Two types of signal for positioning are transmitted from a GPS satellite. One is known as the PN code signal, and the other is the carrier signal. GPS pseudo range corresponds to the distance from the GPS satellite to the receiver. The GPS pseudo range is measured by correlation analysis of PN code signals. On the other hand, GPS Doppler processing yields the relative velocity between a GPS satellite and the receiver. GPS Doppler processing calculates velocity from the frequency shift of the carrier signal.

Figure 3 illustrates a simple example of distance resolution improvement using the two types of GPS signals. In the case of measurement using the PN code signal, the distance resolution is about 300 m. On the other hand, in the case of measurement using the carrier signal, the distance resolution is about 0.2 m. Thus, the distance resolution of the carrier signal is more precise than that of the PN code signal. The carrier signal is used for precise positioning, such as RTK-GPS, which requires a signal received at a base station in order to measure distance. GPS Doppler processing itself isn't able to measure distance. However, it is able to measure precisely changes in distance.

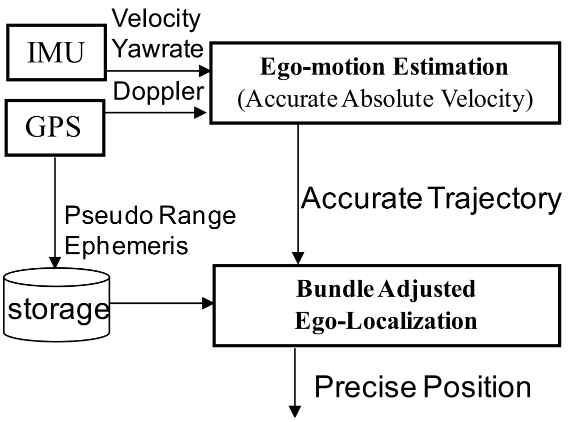
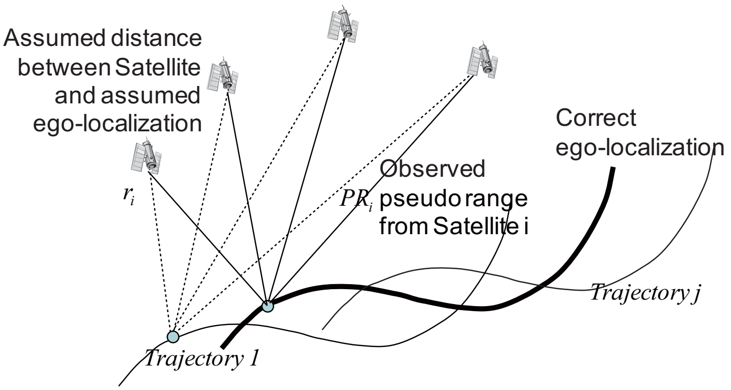


Fig. 1 The concept of our proposal.



$$r_i(t) = \sqrt{(P_i sat(t)_E - Pusr(t)_E)^2 + (P_i sat(t)_N - Pusr(t)_N)^2 + (P_i sat(t)_U - Pusr(t)_U)^2} + Cb(t)$$

Search $Pusr(t)_E, Pusr(t)_N, Pusr(t)_U, Cb(t)$ to satisfy $\min \sum_{t_0-k}^{t_0} \sum_{i}^{N} (PR_i(t) - r_i(t))^2$

Fig. 2 Outline of bundle adjustment.

Figure 4 shows the relationship between absolute vehicle velocity and GPS Doppler shifts. The GPS Doppler shift frequency Di [Hz] is defined in Eqs. 1-2.

$$\begin{aligned} -Di &= f1\frac{C-Vvi+Cbv}{C-Vsi} - f1 \\ &= \frac{f1}{C}\cdot\frac{Vsi-Vvi+Cbv}{1-Vsi/C} \qquad \cdots\cdots\cdots\cdots\cdots (1) \\ &\approx \frac{f1}{C}\cdot(Vsi-Vvi+Cbv) \end{aligned}$$

$$-\frac{Di}{f1}\cdot C = Vsi - Vvi + Cbv \quad \cdots\cdots\cdots\cdots\cdots (2)$$

where Vvi is vehicle velocity and Vsi is satellite velocity, Cbv [m/sec] represents clock bias variation in the GPS receiver, and C [m/sec] is the velocity of light (2.99792458 × 108 m/sec), and $f1$ [Hz] is the frequency of the carrier signal L1(1575.42 × 106 Hz). Vsi and Vvi are defined in Eq. 3.

$$\begin{aligned} Vsi &= \mathbf{R}i\cdot[Vxsi, Vysi, Vzsi]^T \\ Vvi &= \mathbf{R}i\cdot[Vxv, Vyv, Vzv]^T \end{aligned} \quad \cdots\cdots\cdots\cdots\cdots (3)$$

where ($Vxsi$, $Vysi$, $Vzsi$) [m/sec] and (Vxv, Vyv, Vzv) [m/sec] represent 3D vector velocities of GPS satellite i and of the vehicle, respectively, and directional vector Ri is the line of sight between satellite and vehicle, as derived in Eq. 4. In this section, the 3D vector is represented in the ECEF coordinate system.

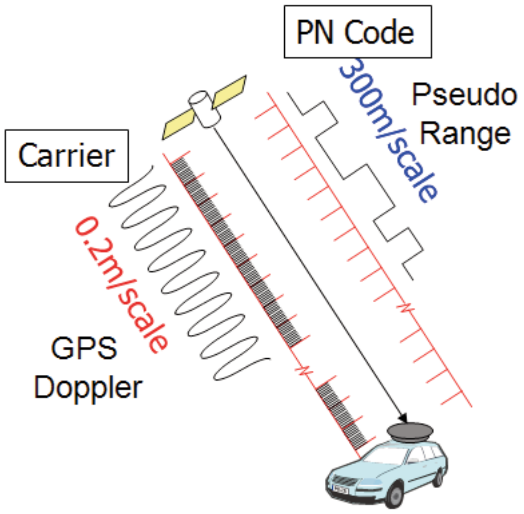


Fig. 3 Example of distance resolution of the PN Code signal and the Carrier signal.

$$\mathbf{R}i = \frac{-1}{ri}\cdot[Xsi-Xv \quad Ysi-Yv \quad Zsi-Zv] \quad \cdots\cdots\cdots\cdots\cdots\cdots (4)$$

where (Xs, Ys, Zs) [m] and (Xv, Yv, Zv) [m] represent the 3D vector position of GPS satellite i and of the vehicle, respectively, and r is the distance between satellite and vehicle, which can be calculated by GPS pseudo range positioning. The vehicle 3D velocity and clock bias variation (Vxv, Vyv, Vzv, Cbv) can be estimated by using Eq. 2 with more than 4 GPS Doppler shifts and GPS satellite 3D velocities. GPS Doppler shift is not affected by the ionosphere and troposphere. Moreover, the directional vector Ri is less affected by vehicle position inaccuracy. Thus, the vehicle velocity Vvi can be accurately determined.

4. 2 Trajectory Estimation by GPS Doppler Processing and Inertial Sensors

Kojima et al.(7) report that accurate vehicle trajectory can be obtained merely by integrating velocities derived by GPS Doppler processing. However, multi-path reflections and blocking of GPS signals occur in urban areas, which decrease velocity accuracy. A method which simply integrates velocities derived from GPS Doppler processing can't determine vehicle trajectory accurately at all times.

To deal with this problem, we considered the heading angle. Eq. 5 shows the relationship between 2D vector trajectory (Te, Tn), vehicle velocity (Vv), and heading angle (ψ). In this section, the 2D vector is represented in an East-North coordinate system.

$$\begin{aligned} Te(t) &= Te(t-1) + Vv\times Sin(\psi(t))\times dt \\ Tn(t) &= Tn(t-1) + Vv\times Cos(\psi(t))\times dt \end{aligned} \quad \cdots\cdots (5)$$

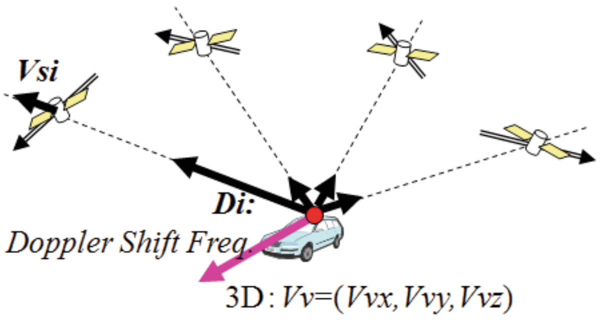


Fig. 4 Relationship between absolute vehicle velocity and GPS Doppler shift.

Heading angle is obtained with Eq. 6. Heading angle is obtained from east and north velocity which can be determined by GPS Doppler processing. Vehicle velocity is measured by an installed speed sensor which is known to obtain accurate speed. Eq. 6 enables vehicle trajectory to be estimated.

$$\psi_{gps}(t)=\tan\left(\frac{Ev(t)}{Nv(t)}\right) \tag{6}$$

In urban areas, however, multipath lowers the accuracy of Eq. 6 results in many places. But there also are places where the accuracy is high. By checking the accuracy and extracting highly accurate headings, robust trajectory estimation is possible.

Figure 5 is an outline of our proposed method, and **Fig. 6** is its flowchart. In this method, heading is estimated from Doppler shifts and yaw rates from the gyro. A key operation is checking heading reliability using Eqs. 7-9. The value that minimizes the difference between the heading from Doppler calculated with Eq. 7 and the heading from gyro azimuth calculated with Eq. 8 is estimated using Eq. 9. A point with low residual variance after this optimization is designated to be a high accuracy heading.

$$\psi(t_0-k)_{gyro}=\psi_{gps}(t_0)-\int_{t_0-k}^{t_0}\dot{\psi}_{gyro}(t)dt \tag{7}$$

$$\min\sum_{t_o-k}^{t_0}\psi_{gps}(t)-\psi_{gyro}(t) \tag{8}$$

$$resi_{\psi(t)}=\psi_{est}(t)-\psi_{gps}(t) \tag{9}$$

5. Poisoning by Bundle Adjustment

Details of the proposed method are as follows. The proposed technique uses the vehicle trajectory for vehicle positioning. Each of the pseudoranges that are received at points which the vehicle has passed on its trajectory are used in the Bundle Adjustment method for positioning. Eq. 10 expresses the position relationships between satellites and the vehicle. Eq. 11 shows vehicle position at time *t*-*k* as estimated from the trajectory. Here, the receiver clock bias is estimated with Eq. 12. If we receive signals from four or more satellites over the whole trajectory, positioning becomes possible.

$$r_i(t)=\sqrt{(P_isat(t)_E-Pusr(t)_E)^2+(P_isat(t)_N-Pusr(t)_N)^2+(P_isat(t)_U-Pusr(t)_U)^2}+Cb^t \tag{10}$$

$$\mathbf{Pusr}(t-k)=\mathbf{Pusr}(t)-\delta\mathbf{T}_{t-k}^{t} \tag{11}$$

$$Cb^{t-k}=Cb^t-\int_{t-k}^{t}Cbv\,dt \tag{12}$$

$$\min\sum_{t_0-k}^{t_0}\sum_{i}^{N}(PR_i(t)-r_i(t))^2 \tag{13}$$

r: Assumed distance between satellite and vehicle
$Pusr$: Vehicle position (East North Up)
$Psat$: Satellite position (East North Up)
$\delta\mathbf{T}$: Vehicle trajectory
Cb: Receiver clock bias
Cbv: Receiver clock drift
PR: Pseudo Range

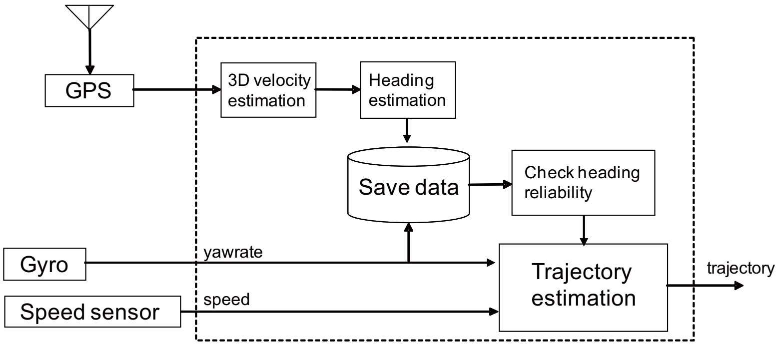


Fig. 5 Outline of the proposed vehicle trajectory estimation technique.

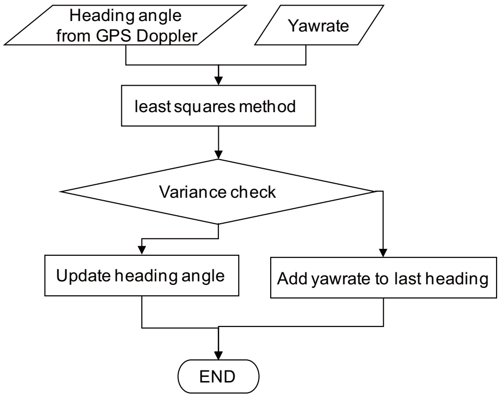
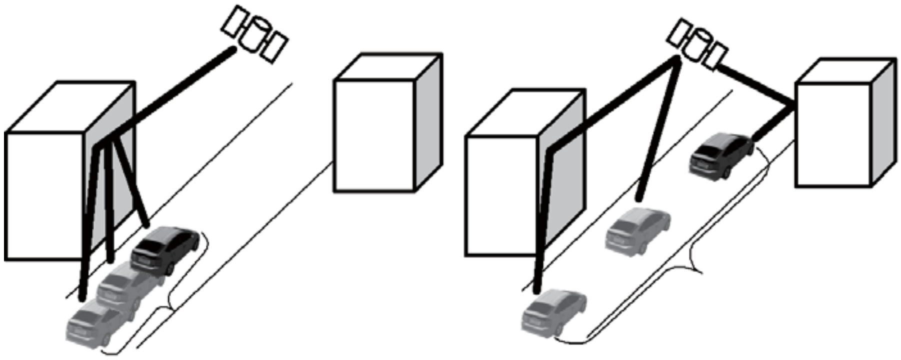


Fig. 6 Flowchart of the proposal vehicle trajectory estimation technique.



a) Time interval b) Spatial interval

Fig. 7 Difference between time and spatial interval.

Bundle Adjustment makes it possible to conduct positioning over the entire trajectory. However, if data obtained from satellites which are not far away from each other are used for positioning, errors from these satellites tend to have similar error trends and so tend to compound each other, since satellite errors due to multipath effect are "location-dependent". Therefore, we propose employing spatial separation, not time, to express the intervals between the satellite signals used for positioning as shown in **Fig. 7**. By employing spatial separation and considering the entire trajectory, the error trends can be prevented from being biased.

The apparent number of satellites can be increased by conducting positioning over the entire trajectory, and taking advantage of this abundance of available satellites, selection of satellites becomes possible. In this basic study, each satellite was assessed, using the residual variance values obtained after their minimization with the above formulas. Specifically, positioning is conducted once for the entire trajectory using all the satellites, and after calculating the residual variances, clustering into classes is conducted. If the average residual variance of a class is larger than the threshold value and the number of members is small, it is determined to be multipath and the satellite in question is rejected.

6. Evaluation Results

An evaluation test was conducted on a road course passing by high-rise buildings and under overpasses in the vicinity of Nagoya Station, Aichi Prefecture, Japan, at about 10 am on July 08, 2010. **Figure 8** shows the evaluation route of about 5.5 km. **Table 1** shows the equipment used for evaluation. Our proposed method

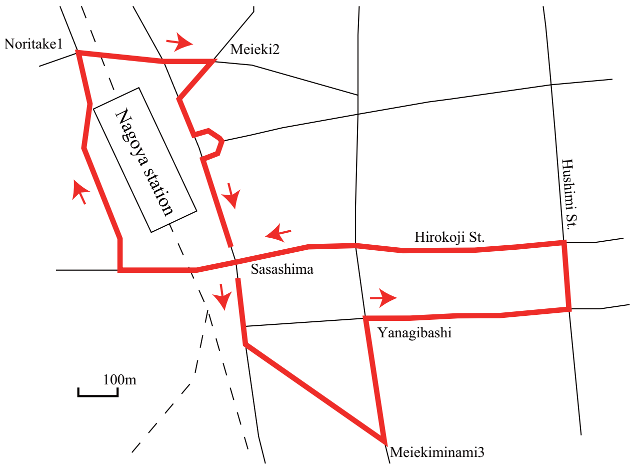


Fig. 8 Evaluation route.

Table 1 Sensor composition.

	GPS Receiver	Gyro
Proposal	OEMV(L1) *1	IMU440(Yawrate)*3
GPS	OEMV(L1) *1	-
LC	OEMV(L1) *1	IMU440(Yawrate)*3
Ublox	LEA-4T*2	-

*1Novatel, *2Ublox, *3CrossBow

uses L1 band which can be received by a generic GPS, a MEMS Yaw rate gyro, and wheel speed sensor. **Figure 9** shows the number of accessible satellites during the test. True positions and velocities were measured by POSLV610(8) that is consist of high accuracy Gyro and GPS and speed sensor.

Figure 10 shows velocity estimation errors by GPS Doppler processing in the field. GPS Multipath causes decreases precision of velocity. **Figure 11** shows velocity estimation errors by our proposed trajectory tracking method described in Chapter 4. Our proposal enables to estimate more accurate velocity. **Figure 12** shows heading estimation errors by GPS Doppler processing. **Figure 13** shows heading estimation errors by our proposed method. Heading is able to be

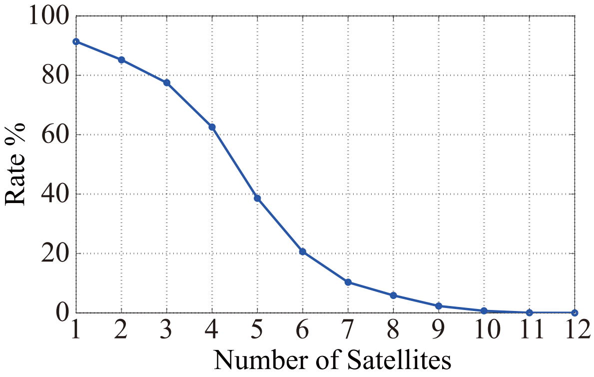


Fig. 9 Number of accessible satellites during the test.

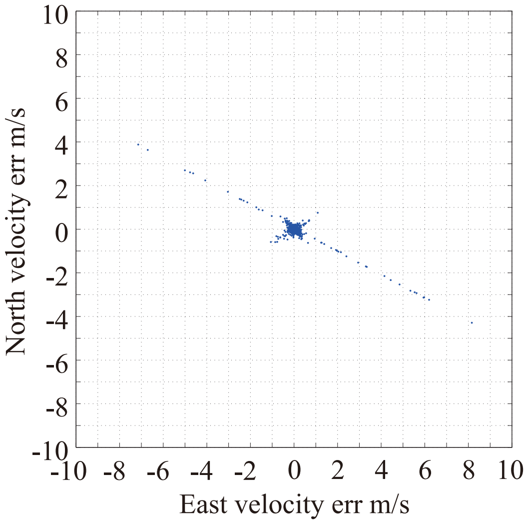


Fig. 10 Velocity estimation error by GPS Doppler.shift processing.

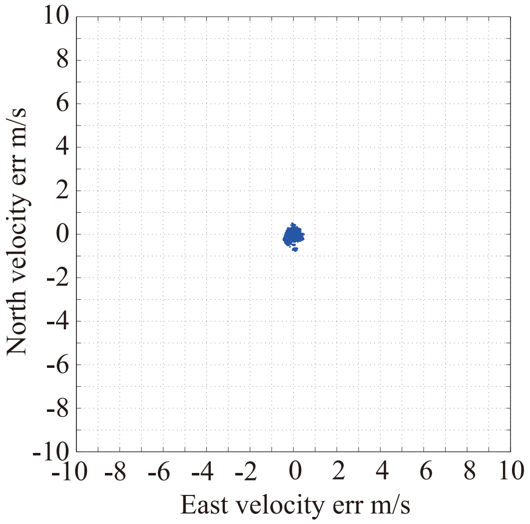


Fig. 11 Velocity estimation error by the proposed method.

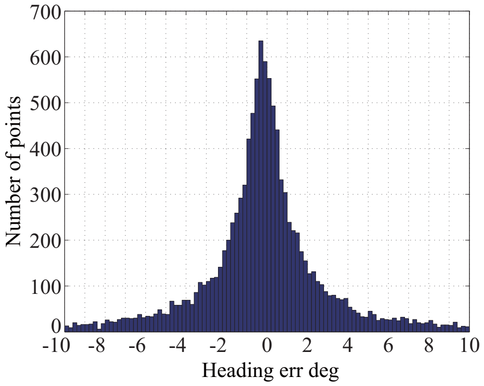


Fig. 12 Heading estimation error estimated by GPS Doppler processing.

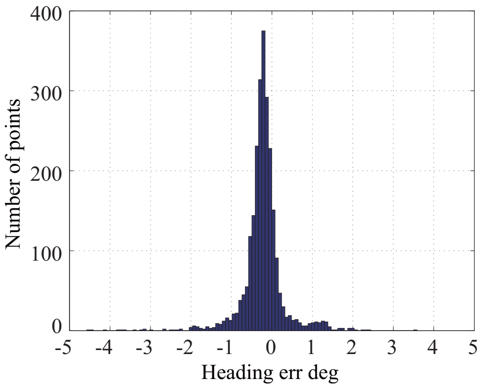


Fig. 13 Heading estimation error estimated by the proposed method.

estimated form velocity in Eq. 6. Accurate heading enables to estimate precise trajectory.

Figure 14 and **Table 2** shows the test results. Here, comparison is made of the performance of our proposed technique, GPS only, Loosely Coupled GPS/IMU (LC), and the Ublox. With GPS only, the positioning accuracy rate was 62 percent lower, because of the signals blocked by surrounding buildings. In addition, the multipath caused 70.3 m (2DRMS) positioning error. With LC, we assume that the GPS error is Gaussian. But the GPS positioning results had a lot of outliers due to multipath. Therefore, the accuracy was 22.5 m (2DRMS). Ublox is a very good product and is a highly sensitive receiver in urban areas. But even it could not completely remove the effects of multipath.

On the other hand, the proposal is able to enhance the positioning accuracy (6.3 m, 2DRMS) due to utilize a sufficient number of satellites along the trajectory. In addition, points aren't impossible to estimate position are interpolated with accurate trajectories.

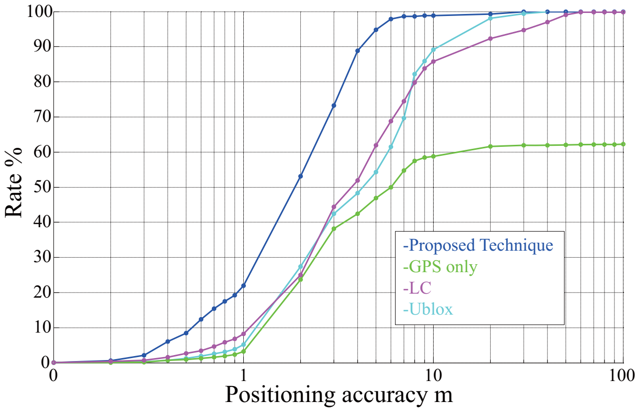


Fig. 14 Positioning accuracy in the evaluation field.

Table 2 Positioning accuracy.

	5m accuracy rate(%)	2DRMS (m)
Proposed	94.8	6.3
GPS	46.8	70.3
LC	63.3	22.5
Ublox	54.3	14.4

7. Conculution

This paper proposes a technique of position estimation which is applicable to urban environments where the accuracy of GPS positioning is deteriorating. The method, utilizing GPS Doppler processing and gyros, calculates trajectories by extracting the most reliable azimuths and then integrating these with the vehicle speeds. The proposed correlates points to integrate the geometry of trajectory and GPS pseudoranges which are received at various places along the whole trajectory. Using the pseudoranges obtained in the past, it is possible to judge the confidence level of the positioning. This makes it possible to select the best satellites for positioning.

In the evaluation test on a road course passing by high-rise buildings and under overpasses in the city area, our proposed method exhibited better accuracy of position estimation than conventional methods, demonstrating its effectiveness.

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