A Study on GPS Positioning Method with Assistance of a Distance Sensor

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***Abstract*—In order to estimate a receiver's position, a Global Positioning System (GPS) receiver has to receive the signals from at least four observable satellites. However, in urban areas, the number of the observable satellites decreases because urban areas have many buildings. In such cases, the position estimation cannot be performed well. So, our research considers position estimation in case that the observable satellites are decreased. Many vehicles have the distances sensors which can measure traveling distance. Our proposal can estimate own position by using the traveling distance and the previous position which is estimated under good GPS condition. Our experimental results will show our effectiveness of the proposal.**

Keywords–GPS; Positioning; Urban canyon; Lack of observable satellites.

I. Introduction

In recent years, location-based services have been increasing. Many of these services require the information of user's position. Car navigation systems can be given as an example. In general, these services use the Global Positioning System (GPS). GPS is a system that can estimate user's position by using flying satellites around the Earth.

The position estimation by GPS calculates the position, based on the measurement of the distances between the GPS receiver and the GPS satellites. In order to perform the position estimation, GPS receiver requires at least four satellites which can be received in line-of-sight [1]. However, in urban areas, the number of the observable satellites decreases because of the buildings. These situations are called urban canyon. In urban canyon, GPS signals from observable satellites tend to degrade because of multi-path propagation. The signals via multi-path should not be used because the errors are included in the propagated paths. In order to avoid multi-path signals, the number of direct-path satellites which we prefer to use is more decreased. In such cases, the position estimation cannot be performed well. For example, the estimator cannot estimate the receiver's position if the number of observable satellites becomes less than three. Or, the performance becomes worse compared to the conditions in open sky where we can observe more than four satellites. Actually, conventional GPS systems rely on other information such as map information, base stations of 3G cellular networks, or Wi-Fi networks against the bad GPS measurement. The positioning method which does not rely on other information is desired because the simple positioning should not use big data and wireless links to get other information.

So, our research considers the position estimation in the case that the observable satellites are decreased. Many vehicles have wheel rotation sensors which can measure the traveling distances. We propose the novel positioning method which uses the information of the previous traveling distance [2][3]. Our proposed method uses the information of both the distance sensor and the previous position which is estimated under good condition, to GPS positioning. Higher accuracy in position estimation is expected by our proposed method, even when the number of observable satellites is decreased. Also, it can be expected to prevent the position estimation impossibility when the number of the observable satellites becomes three.

In this paper, we will show the case that the number of the observable satellites becomes three as the worst case to introduce and evaluate our proposed method. Here, the position estimation is performed by traveling on a bicycle. Using experimental results, we will show the effectiveness of our proposed method.

This paper organized as follows. In Section II, we will introduce related works briefly. In Section III, we will show our proposal in detail. In Section IV, we will present the proposal's performance by field experiments. Finally, Section V summarizes the paper.

II. Related Work

In this section, we will show the related methods to improve the accuracy of the position estimation. Here, we are introducing the traditional and basic technologies.

A. Differential GPS (DGPS)

The Differential GPS (DGPS) is the method for improving the position estimation accuracy [4]. The DGPS uses the GPS base station. The GPS base station transmits the information of the error amount in the GPS measurement to near GPS receivers. Measuring of the error information is performed accurately at the GPS base station.

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Generally, the position estimation by GPS calculates the position by using the measurement of the distances between the GPS receiver and the GPS satellites. However, some errors are included in the distance measurement. The distance errors by clock difference, the ionospheric delay, and the troposphere delay can be given as examples. The estimation accuracy of user's position can be improved by correcting the error information which is generated at the GPS base station. However, the GPS estimation is used in various locations, such as urban areas, rural areas, sea, and mountains. In the urban areas, the DGPS cannot correct the propagation delay caused by the reflection at buildings. Therefore, in such case, the position estimation cannot be performed well.

B. Dead Reckoning (DR)

The Dead Reckoning (DR) is the method of performing position estimation by the information of the relative movement [5]. In other words, DR uses the information how much we traveled from the previous position. Since the DR does not require any infrastructures, the DR is not limited to any area.

In vehicles, various sensors exist to detect the direction. Usually, the angular velocity is detected by the angular velocity sensor. The angular velocity can be calculated by integrating the traveling direction [6]. Also, it is possible to detect the direction by using a fiber optic gyroscope. The fiber optic gyroscope is a device for determining the direction by measuring the time difference of the light when the angular velocity is added to the fiber optic.

By using vehicle speed pulses, it is possible to detect the traveling distance. The vehicle speed pulse is the signal which is generated according to the rotational speed of the drive shaft of the vehicle. We can measure the traveling distance based on the circumference of the tire and the vehicle speed pulse.

In the DR, the relative position can be estimated by using the moved direction and the traveled distance. The DR is often used with a map matching technique, as described in the next section. The combination of both DR and map matching are often used in the car navigation systems.

C. Map Matching

The map matching is the method for finding the appropriate position of the vehicle on the road by using the map information [7]. It is used in combination with the position estimation methods such as GPS and DR.

Currently, the map matching and the DR are commonly used in the car navigation systems [8]. The DR is a system for determining the relative position from the previous position. In DR, the error accumulates when the error occurs in the distance sensor and the direction sensor. This problem can be solved by using the map matching, but the map matching cannot be used in a place which does not have the map information. So, in order to estimate the absolute position, the DR with the map matching is often used with GPS. However, the sensor data from the DR does not improve the positioning accuracy of GPS directly.

As a new method, we want to improve the position estimation accuracy by adding the sensor data, to the GPS position estimation directly. Here, we use a distance sensor. We proposed the positioning method which can estimate the absolute position by the combination of the distance sensor and GPS [2][3]. By our proposed method, the absolute position can be estimated even if only GPS cannot estimate own position because of the bad environment. The bad environment for the conventional GPS is under lack of the observable satellites. This case often happens in urban areas. In our proposal method, we can keep estimating the user's absolute position by assistance of the distance sensor.

III. Proposed Method

In this section, first, we will show the problems of the position estimation by GPS. Thereafter, we will show our proposed method which uses the distance sensor and the previous position information.

A. Problems of Position Estimation by GPS

The GPS positioning estimates the receiver's position based on the distances between the receiver and the satellites [9]. For estimating the 3D position of the receiver, the receiver needs three relations, that is, three satellites. Moreover, the receiver needs to estimate own clock error because the general receivers are equipped with inexpensive crystal clocks. Therefore, the GPS position estimation needs four relations, that is, four satellites. For carrying out the positioning calculation, the GPS position estimation needs at least four observable satellites. The observable satellite means the satellite which can receive its signal in line-of-sight. However, in urban areas, the number of the observable satellites is decreased because the receiver cannot observe the low elevation satellites due to the interference of buildings. Therefore, the receiver is not always possible to observe more than or equal to the four satellites in line-of-sight. So, the number of the observable satellites tends to decrease. Such decrement results in degradation of the position estimation accuracy. As a worst case, the receiver cannot estimate its own position if the number of the observable satellites becomes less than four. This is the most common problem in urban area.

To solve the above problem, we propose the novel GPS estimation which uses the distance sensor and the previous position information. The proposal method uses the previous receiver's position. We can measure the traveling distance from the previous position by the distance sensor. We assume the previous position as the quasi-satellite which uses both the previous position and the traveled distance. By the proposed method, we expect that the position estimation is possible even if the number of the observable satellites are three. In addition, we also expect the improvement of position estimation accuracy when the number of the observable satellites are low. The detailed procedure is shown in the next subsection.

B. Proposed Position Estimation Algorithm

The proposed method is assumed to be used in position estimation on vehicles such as cars or bikes. The assumed situation of our research is shown in Figure 1. We consider 2 observation times (the time t and $t + \tau$). The position coordinate of the receiver at the time t is (x_0, y_0, z_0). And the position coordinate of the receiver at the time $t + \tau$ is (x, y, z). We want to estimate the position (x, y, z). We define that the position of the i-th satellite is (x_i, y_i, z_i).

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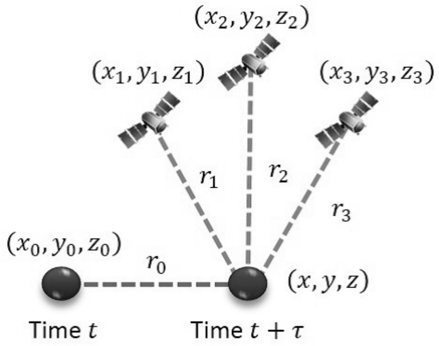

Figure 1. Assumed situation of our research.

By using the orbital information of the satellites which is contained in the satellite signals, the positions of the satellites can be defined. Also, the variables $r_i(i = 1, 2, 3)$ are the distances between the receiver and the satellites. On the other hand, the variables r_0 is the distance between the time t position and the time $t + \tau$ position. Here, we assume that the position was correctly estimated by the adequate satellites at the time t. After traveling, we assume that the observable satellites are decreased at the time $t+\tau$. The number of the observable satellites at the time $t+\tau$ are assumed as three. In this case, the position estimation becomes impossible because of lack of observable satellites.

In this paper, for the purpose of simple explanation, we assume that the number of the observable satellites are four at the time t. The GPS positioning at the time t uses the satellite positions and the distances between the receiver and the satellites. The true distance ρ_i between the i-th satellite and the receiver can be expressed as follows.

$$\rho_i = \sqrt{(x_i - x_0)^2 + (y_i - y_0)^2 + (z_i - z_0)^2} \quad (1)$$

The clock error may be included to the distance between the receiver and the satellite. Therefore, the distance r_i can be expressed by (2).

$$r_i = \rho_i + s \quad (2)$$

Here, the clock error is represented as the parameter s. The unit of clock error s is meter. This equation can be applied to all the observable satellites. As the number of the observable satellites are four at the time t, the following four equations can be obtained.

$$\begin{cases} r_1 = & \rho_1 + s \\ r_2 = & \rho_2 + s \\ r_3 = & \rho_3 + s \\ r_4 = & \rho_4 + s \end{cases} \quad (3)$$

By solving (3), it is possible to find out the position of the receiver (x_0, y_0, z_0) and the clock error s [10].

In case of the time $t + \tau$, the above method is not applicable for the position estimation because the number of the observable satellites are three. Therefore, we will estimate the position (x, y, z) by adding the quasi-satellite. That is, we use the previous position (x_0, y_0, z_0) and the distance between the current position and the previous position r_0. The distance r_0 can be represented by (4).

$$r_0 = \sqrt{(x_0 - x)^2 + (y_0 - y)^2 + (z_0 - z)^2} \quad (4)$$

At the time $t + \tau$, we can observe the three satellites. So, we can obtain the three equations (2). By using the three relations based on (2) and (4), we can derive the following equations.

$$\begin{cases} r_1 = & \sqrt{(x_1 - x)^2 + (y_1 - y)^2 + (z_1 - z)^2} + s \\ r_2 = & \sqrt{(x_2 - x)^2 + (y_2 - y)^2 + (z_2 - z)^2} + s \\ r_3 = & \sqrt{(x_3 - x)^2 + (y_3 - y)^2 + (z_3 - z)^2} + s \\ r_0 = & \sqrt{(x_0 - x)^2 + (y_0 - y)^2 + (z_0 - z)^2} \end{cases} \quad (5)$$

It is possible to estimate the position (x, y, z) by (5).

The advantage of the proposed method is that we can increase the available satellites by adding (4). In addition, the proposed method only uses the GPS receiver and the distance sensor, no other infrastructure is needed. In our proposal, we need the distance between the current position and the previous position. In recent vehicles, it is easy to measure the traveling distance because most of the vehicles have distance sensors, such as speed pulses.

C. Calculation Process of Position Estimation

Because the simultaneous equation (5) is nonlinear, the solution can be obtained by the sequential approximation that is performed the linearization around the initial value. Here, the procedure of the sequential approximation is shown below. As a notation, subscripts of the right shoulder of the following variables indicate the times of the sequential approximation.

1) we prepare the suitable initial values x^0, y^0, z^0, s^0 about x, y, z, s.
2) By using the receiver position x^0, y^0, z^0 and the clock error s^0, we calculate the distances between the receiver and the satellites.

$$\begin{cases} r_1^0 = \sqrt{(x_1 - x^0)^2 + (y_1 - y^0)^2 + (z_1 - z^0)^2} + s^0 \\ r_2^0 = \sqrt{(x_2 - x^0)^2 + (y_2 - y^0)^2 + (z_2 - z^0)^2} + s^0 \\ r_3^0 = \sqrt{(x_3 - x^0)^2 + (y_3 - y^0)^2 + (z_3 - z^0)^2} + s^0 \\ r_0^0 = \sqrt{(x_0 - x^0)^2 + (y_0 - y^0)^2 + (z_0 - z^0)^2} \end{cases} \quad (6)$$

3) The residual error $\Delta r_i = r_i - r_i^0$ can be determined by using the distance $r_i(i = 0, 1, 2, 3)$ which is actually measured.
4) Since it is possible to approach the correct solution by compensating same amount corresponding to the residual error for x^0, y^0, z^0, s^0, the compensation amount is determined using the partial derivative about x, y, z, s.

$$\begin{aligned} \frac{\partial r_i}{\partial x} &= -\frac{(x_i - x)}{r_i} \\ \frac{\partial r_i}{\partial y} &= -\frac{(y_i - y)}{r_i} \\ \frac{\partial r_i}{\partial z} &= -\frac{(z_i - z)}{r_i} \\ \frac{\partial r_i}{\partial s} &= \begin{cases} 1(i = 1, 2, 3) \\ 0(i = 0) \end{cases} \end{aligned} \quad (7)$$

From (7), the compensation amount $\Delta x, \Delta y, \Delta z, \Delta s$ to update x^0, y^0, z^0, s^0 can be represented as follows.

$$\begin{cases} \Delta r_1 = & \frac{\partial r_1}{\partial x}\Delta x + \frac{\partial r_1}{\partial y}\Delta y + \frac{\partial r_1}{\partial z}\Delta z + \frac{\partial r_1}{\partial s}\Delta s \\ \Delta r_2 = & \frac{\partial r_2}{\partial x}\Delta x + \frac{\partial r_2}{\partial y}\Delta y + \frac{\partial r_2}{\partial z}\Delta z + \frac{\partial r_2}{\partial s}\Delta s \\ \Delta r_3 = & \frac{\partial r_3}{\partial x}\Delta x + \frac{\partial r_3}{\partial y}\Delta y + \frac{\partial r_3}{\partial z}\Delta z + \frac{\partial r_3}{\partial s}\Delta s \\ \Delta r_0 = & \frac{\partial r_0}{\partial x}\Delta x + \frac{\partial r_0}{\partial y}\Delta y + \frac{\partial r_0}{\partial z}\Delta z \end{cases} \quad (8)$$

Here, the simultaneous equation (8) can be represented by the matrix form in order to simplify handling. We define the vectors $\Delta\vec{x} = [\Delta x, \Delta y, \Delta z, \Delta s]^{\mathrm{T}}$ and $\Delta\vec{r} = [\Delta r_1, \Delta r_2, \Delta r_3, \Delta r_0]^{\mathrm{T}}$ (the notation T expresses a transpose) , the equation (8) can be expressed as follow.

$$G\Delta\vec{x} = \Delta\vec{r} \tag{9}$$

Here, the matrix G is usually called as the observation matrix or the design matrix. The matrix G can be expressed as follows.

$$G = \begin{bmatrix} \frac{\partial r_1}{\partial x} & \frac{\partial r_1}{\partial y} & \frac{\partial r_1}{\partial z} & \frac{\partial r_1}{\partial s} \\ \frac{\partial r_2}{\partial x} & \frac{\partial r_2}{\partial y} & \frac{\partial r_2}{\partial z} & \frac{\partial r_2}{\partial s} \\ \frac{\partial r_3}{\partial x} & \frac{\partial r_3}{\partial y} & \frac{\partial r_3}{\partial z} & \frac{\partial r_3}{\partial s} \\ \frac{\partial r_0}{\partial x} & \frac{\partial r_0}{\partial y} & \frac{\partial r_0}{\partial z} & \frac{\partial r_0}{\partial s} \end{bmatrix}$$
$$= \begin{bmatrix} -\frac{(x_1-x)}{r_1} & -\frac{(y_1-y)}{r_1} & -\frac{(z_1-z)}{r_1} & 1 \\ -\frac{(x_2-x)}{r_2} & -\frac{(y_2-y)}{r_2} & -\frac{(z_2-z)}{r_2} & 1 \\ -\frac{(x_3-x)}{r_3} & -\frac{(y_3-y)}{r_3} & -\frac{(z_3-z)}{r_3} & 1 \\ -\frac{(x_0-x)}{r_0} & -\frac{(y_0-y)}{r_0} & -\frac{(z_0-z)}{r_0} & 0 \end{bmatrix} \tag{10}$$

The compensation amount $\Delta x, \Delta y, \Delta z, \Delta s$ in (8) can be derived by multiplying the inverse matrix of G from the left of (9). Therefore, the compensation amount $\Delta x, \Delta y, \Delta z, \Delta s$ can be determined by solving (11).

$$\Delta\vec{x} = G^{-1}\Delta\vec{r} \tag{11}$$

5) The initial values x^0, y^0, z^0, s^0 are updated by $\Delta x, \Delta y, \Delta z, \Delta s$ as follows.

$$\begin{aligned} x^1 &= x^0 + \Delta x \\ y^1 &= y^0 + \Delta y \\ z^1 &= z^0 + \Delta z \\ s^1 &= s^0 + \Delta s \end{aligned} \tag{12}$$

6) After updating the initial value to x^1, y^1, z^1, s^1, we return to the Procedure 2. These procedures are repeated until $\Delta x, \Delta y, \Delta z, \Delta s$ becomes enough small.

By following the above procedure, our proposed method has the possibility to calculate the receiver's position (x, y, z). In our experience, the solution can converge by repeating several times even if the initial values are $x^0 = y^0 = z^0 = s^0 = 0$.

IV. The Characterization by Field Experiment

A. Setup and Environment

The experiments were conducted in order to evaluate the ability and the effectiveness of the proposed method. In the proposed method, the position estimation is performed while updating the traveling distance and the previous position. The assumed environment is an urban area. There are many buildings in urban areas. The satellites with low elevations tend to be shaded by the buildings. So, we trust only the satellites with high elevations.

In the experiment, we are using a bicycle as the moving vehicle. The bicycle is shown in Figure 2. As shown in Figure 2, a GPS antenna is attached to the loading platform. Also, the cycle computer is attached to the front wheel. The cycle computer is shown in Figure 3. The cycle computer is a device which senses a magnet mounted on the spokes of the tire to generate a pulse after each rotation. The bicycle also has a data logger system. Each generated pulse is saved in the data logger. The sampling interval of the data logger is 1 ms. The example of the saved pulses is shown in Figure 4. From Figure 4, the cycle computer outputs 0V when the magnet passes the front of the sensor. Except above, the cycle computer usually outputs 2V. We can recognize the rotation of the tire by the pulses. Based on these pulses, the distance r_0 can be measured. The duration between an edge of a pulse and that of the next pulse is equal to the circumference of the tire. The traveling distance r_0 is calculated for each position estimation by using the circumference of the tire.

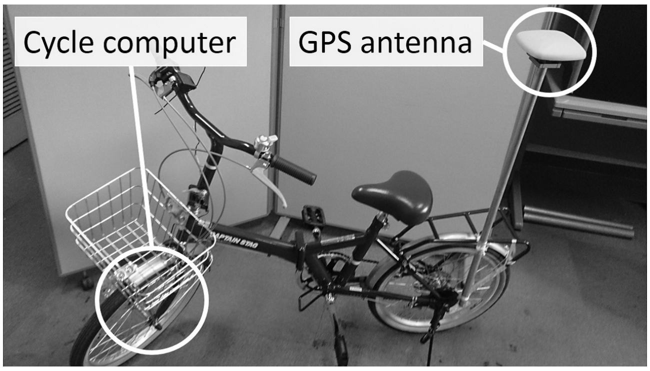

Figure 2. Experimental vehicle.

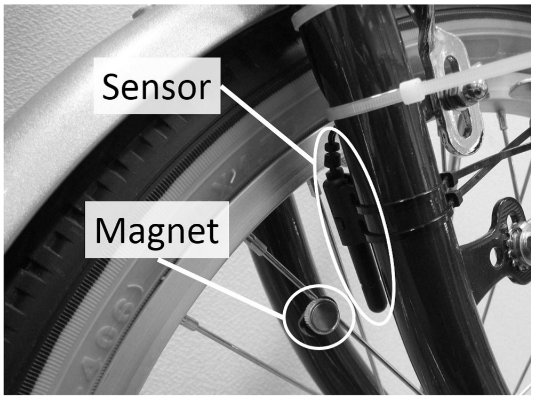

Figure 3. Cycle computer.

The experiment has been conducted under an open sky. The distance r_0 had measured while traveling by the bicycle. The position estimation of the proposed method is performed using the three satellites with high elevation and the previous position. For comparison, the positions are also estimated by the conventional method with all the observable satellites.

A total distance of the experimental riding is 100 meters. In the first 20 meters, we rode toward east straightly. Then, we turned right. In the next 80 meters, we rode toward south straightly again. The cycle computer has a function that displays the speed according to the rotational speed of the tire. We kept the speed of the bicycle 10 km/h. From the start to the end, the time is 50 seconds. Table I summarizes the parameters of the experiment environment.

By using the data obtained in the experiment, the position estimation is performed per second. The GPS

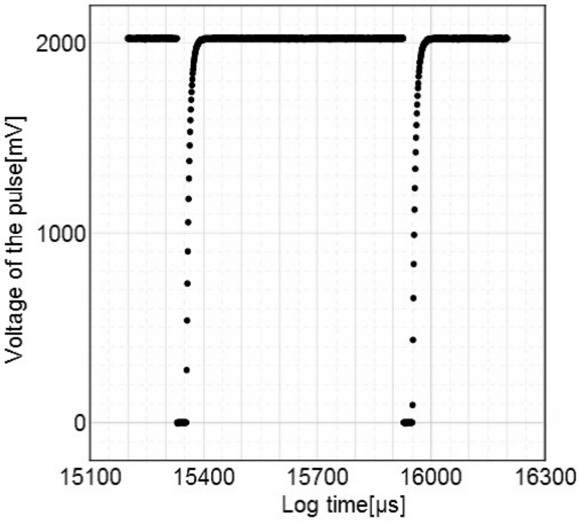

Figure 4. Waveform from the cycle computer.

TABLE I. SPECIFICATIONS OF THE EXPERIMENT ENVIRONMENT

GPS receiver	JAVAD GNSS DELTA-G3T
Number of observable satellites	8 satellites
Total traveling time	50 s
Estimation interval of GPS receiver	1 s
Data logger	EasySync DS1M12
Cycle Computer	CATEYE CC-VL820 VELO 9
Sampling interval of the data logger	1 ms
Circumference of the tire of the bicycle	1.515m

receiver can output the distance between the receiver and the satellites. The output distance includes some errors, such as the ionospheric delay error and the tropospheric delay error (so, the output distance is often called as the pseudo range). The ionospheric delay can be estimated by the transmitted messages from the satellites because the messages have coefficients of equations which are modeled as the ionospheric delay. So, we subtract the modeled ionospheric delay from the output distance. Similarly, we subtract the modeled tropospheric delay from the output distance. We use the remaining distance as the distance r_i For comparison, the position estimation using all satellites was also calculated per second. In the proposed method, the position coordinates of the start is estimated by using the four satellites with high elevation.

B. Position Estimation Results

Figure 5 shows the results of the proposed and conventional method of position estimation. The origin of Figure 5, is the starting point. The positioning results are plotted every second. According to Figure 5, by using the proposed method, the position estimation can be performed even when the number of the observable satellites are three. First, the bicycle is moving towards east, from the start point. After going 20 meters straightly, the direction is changed to the south. Finally, the bicycle stops when the traveling distance becomes 80 meters from the turned point. As we can see, the proposal method can keep estimating the position when the direction of the traveling is changed while traveling.

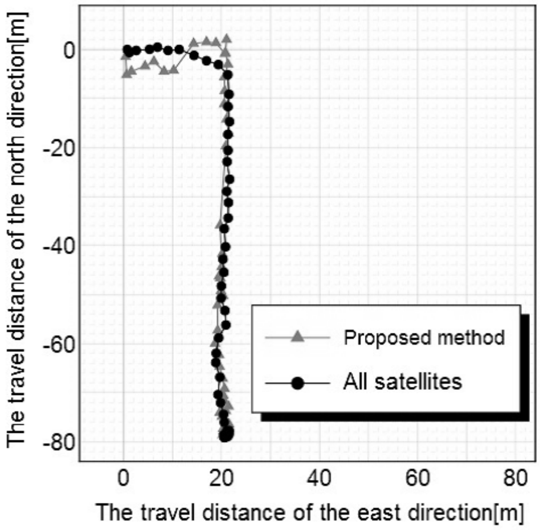

Figure 5. Position estimation results of all satellites and the proposed method.

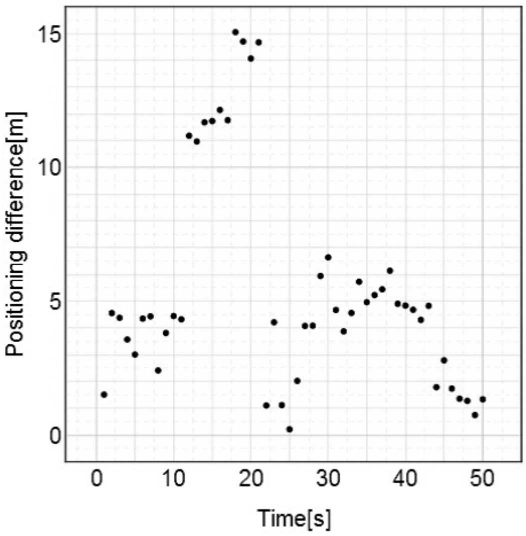

Figure 6. Positioning difference.

In Figure 6, the positioning difference between the estimated position by the proposed method and the position by all the satellites is shown. The positioning difference is defined as Euclidean distance between both the positions. Figure 6 is plotted every second. The total traveling time is 50 seconds. The positioning difference is 5 meters or less until 11 seconds from the start time. In addition, from 22 seconds to 50 seconds, the positioning difference also under 5 meters. Also, the few samples are 7 meters or less. From 12 seconds to 21 seconds, the positioning difference is over 10 meters.

As another viewpoint of discussion, Figure 7 shows the cumulative probability distribution in order to check the distribution of the positioning difference. From Figure 7, 76 percent of the positioning differences are 5 meters or less. The rate of the positioning differences over 10 meters is about 17 percent.

By considering these results, the proposed method is able to estimate the receiver's position by using the previous position and the three satellites with high eleva-

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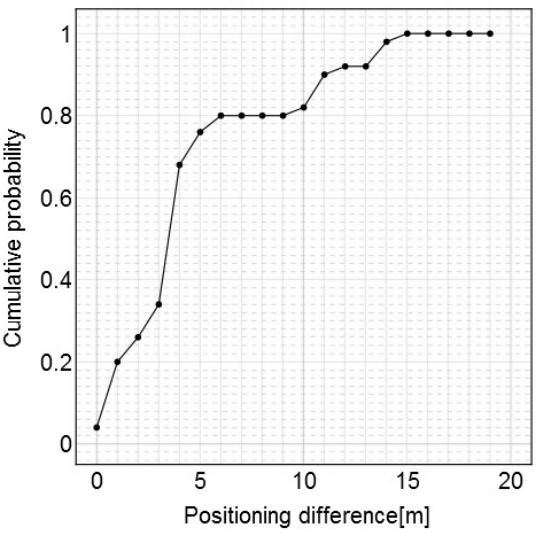

Figure 7. Cumulative probability distribution of the positioning difference.

tion. However, there are some cases when the positioning differences are more than 10 meters. These large differences are a problem which will have to be resolved. One of the above reasons is the satellites constellation. Generally, in case of the four satellites, the good satellites constellation can be presented as follows [11].

- One satellite is near zenith, that is, with high elevation.
- Other three satellites are distributed and surrounded uniformly with low elevations.

In this experiment, three satellites with high elevation have been selected. A better selection has to be consider for the above appropriate satellite constellation. By a better selection, we expect that the proposal can become better.

We now investigate other reasons why the large differences occur. In this paper, the properties were evaluated by comparing the position estimation results of using all satellites. However, the measurement error of the estimation results by all satellites may be included. In oder to investigate in more detail, it is necessary to evaluate the characteristics by comparing the true position with the proposed method.

The proposed process is not much different from the conventional process. In the proposed method, we just use the traveling distance instead of the range from a satellites. So, there is no big difference in calculation time compared to the conventional positioning. We hope that our proposal can be calculated in real-time.

V. Conclusion

In this paper, our proposal was to make position estimation possible in places where the observable satellites are decreased. In order to compensate the decrement, our proposed method assumed the previous own position as the quasi-satellite. For using the previous position as the quasi-satellite, we needed the traveling distance from the previous position. So, we focused on the traveling distance sensor which general vehicles have. By using the distance sensor, we proposed the position estimation method which can keep estimating own position even when the number of the observable satellites becomes low. In order to evaluate the proposed method, the positioning experiment was done using the bicycle. Through the experimental results, possibility of the position estimation and the characteristic of the position estimation were shown when the proposed method is used. Also, there were some cases where the position estimation error was larger than expected. As a future work, we have to consider the reason of the large error and will provide countermeasures.

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