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Design and Analysis of a Simple GPS Code Information-based Relative Positioning Assistant Algorithm*

XU Shenglei and Sangsun LEE

(*Division of Electrical and Computer Engineering, Hanyang University, Seoul, South Korea*)

Abstract — Many vehicle application services called LBS (Location based services) are currently based on location information, but civil location equipment is either too expensive or the positioning accuracy is not high enough to provide LBS. If each vehicle used as a center can precisely calculate the relative positions of other vehicles, LBS can be more easily provided. Based on this premise, a new method by limiting low-cost GPS receivers and communication satellites into similar environment respectively to calculate the relative position with a higher accuracy is proposed in this study.

Key words — Location based service, GPS positioning, Absolute positioning, Relative positioning, DGPS, Relative distance.

I. Introduction

The automotive industry has developed very rapidly in recent decades. As the performance of cars has improved and prices have declined, people have become inconvenienced without a vehicle. Vehicles are a part of daily life and work, and thus, have become an indispensable tool.

As vehicles are used more frequently and the automotive manufacturing and sales industries develop rapidly, more automotive research, especially automotive applications research, is being conducted. Many projects related to vehicles have been performed recently or are underway including the VSC-A and IntelliDrive projects in the USA, the SAFESPOT and Car2Car-CC projects in Europe, the VMC and Smart-Highway projects in South Korea, and the Smartway project in Japan. Most of these projects aim to enhance transportation safety and to provide convenience to the user. Some classic examples of automotive application services provided by these projects include the Safe Speed and Safe Following Service, Rear End Collision and Frontal Collision Warning Service, Emergency Vehicle Approaching Warning Service, Emergency Vehicle at Scene Warning Service, Post-crash/Breakdown Warning Service, Pre-crash Sensing Service, and the Cooperative （Forward） Collision Warning Service. Some of these services aim to notify the driver to maintain a certain distance from neighboring cars or to maintain a certain driving speed while others aim to notify the driver of emergency obstacles or sites, or dangerous elements.

All of these services have the common characteristic of requiring knowledge of their own and surrounding vehicles' positions. Obviously, improved accuracy of the vehicle positions is beneficial. However, since high-precision single-point positioning equipment is expensive and services can be provided only if the relative positions of the automobile and other vehicles are known, we attempted to accomplish highly accurate relative positioning using low-precision single point positioning equipment in this study. The overview of positioning technology is introduced in Section II and after discussing GPS positioning technologies in Section III, we introduce our proposed relative positioning algorithm in Section IV. Section V discusses the testing procedure and results of the proposed algorithm. Finally, we present our plans for future work in Section VI.

II. Overview of Positioning Technology

Many technologies have been developed to obtain relative position information, but they aren't suitable for your vehicular relative positioning.

In Infrared-based positioning, the IR sensor, as previously described[1,2], has poor range resolution and is only applicable for short distances (under 25cm). A sensor with an accuracy of 0.5cm has been demonstrated[3], but it uses a priori known passive reflectors as position references. Several IR-based distance sensors were analyzed and compared[4], but none of these are fully satisfactory for transportation applications as they are better suited for positioning in an indoor environment.

Ultrasonic positioning system requires the use of many references to locate objects in an actual indoor environment since an ultrasonic signal can usually propagate less than five meters and does not penetrate obstacles. As a result, ultrasonic positioning systems can be highly accurate in an indoor environment, but are not suitable for transportation environment positioning.

Bluetooth (over IEEE802.15.1), Ultra-wideband (UWB, over IEEE802.15.3), ZigBee (over IEEE 802.15.4), and Wi-Fi

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(over IEEE 802.11) can also be used for positioning[5], but they were originally designed for other purposes. Bluetooth is intended for use in applications such as cordless mice, keyboards, and hands-free headsets. UWB is oriented to high-bandwidth multimedia links and ZigBee is designed for reliable wirelessly networked monitoring and control networks. Wi-Fi is used to facilitate computer-to-computer connections as an extension of or substitution for cabled networks[6]. Because of their characteristics, they work well in indoor environments but perform poorly in outdoors such that they cannot be used in the automotive service applications mentioned in Section I.

The cellular network is an example of mobile positioning technology. In the CDMA (Code division multiple access) system, different users can share the same frequency by using different spreading codes. This method yields high capacity but also causes multi-access interference and the near-far effect. Multi-access interference can significantly affect the coarse capture of TOA and TDOA information, and greatly influences the time measurement of the delay phase-locked loop[7]. Power control is commonly used to overcome the near-far effect in CDMA systems but it is only useful for a service station because a mobile station is still influenced by multi-access interference, which affects the measurement of the TOA or TDOA values[8]. The complexity of the mobile communication system network architecture and the coexistence of multiple air interface standards increase the difficulty of achieving high-precision positioning[9].

Another mobile positioning technology is Global Positioning System-based (GPS-based) positioning technology. This technology has been researched since 1978 when the first satellite was successfully launched for GPS systems by the United States. Considerable achievements in the application of the GPS have been accomplished over the last 30 years[10]. The GPS provides navigation, positioning, timing, and velocity measurement systems, and it functions globally in any weather on land, water, or in the air. In addition, GPS devices do not have the coexistence of multiple air interface standards problem. Therefore, GPS-based positioning technology has been widely used.

The problem with high-precision GPS receivers is that they are either used for military applications or are too expensive. The accuracy of civilian GPS receivers is not high enough to meet the needs of high-precision location services including automotive application services. Therefore, in this study, we focused on the use of current GPS location information to obtain more accurate relative location information for automotive application services.

III. GPS Positioning Technologies

There are two basic GPS positioning technologies. One is GPS absolute point positioning, which is also called single point positioning, and the other is differential positioning, which is also called relative positioning. Compared to absolute point positioning, differential positioning positions two stations relative to each other (hence, the term "relative positioning") and can provide the higher accuracy required for project control, topographic, and hydrographic surveys. There are two basic general types of differential positioning: the code pseudo-range tracking method and the carrier phase tracking method[11].

Code pseudo-range tracking is the most widely used differential GPS positioning technique. This technique is very similar to absolute positioning techniques. The clock biases and propagation delays due to atmospheric conditions are significantly minimized when the code phase observations are made with two receivers. This allows for a relatively accurate pseudo-range correction to be computed at the receiver station set over a known point. If the pseudo-range correction is computed for four satellites and is transmitted to the user's receivers, the user's receivers can correct the raw pseudo-ranges originally observed and the positioning accuracy will be improved. The process for this technique is shown in Fig.1.

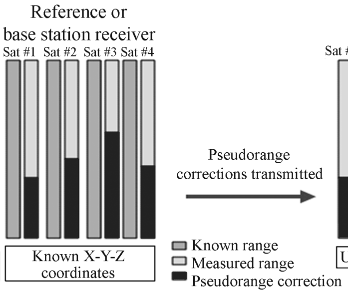
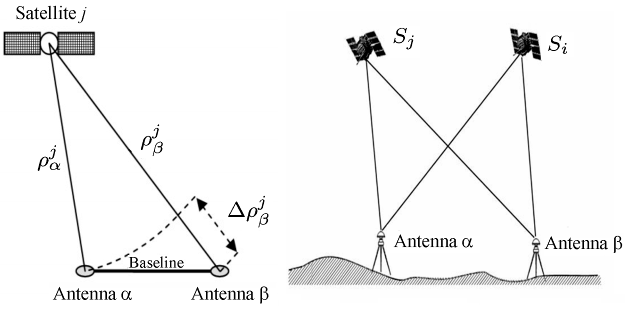


Fig. 1. DGPS concept: code pseudo-range tracking



(a) Single difference (b) Double difference

Fig. 2. Differential calculation

For carrier phase tracking, GPS receivers measure what is termed the "observable" carrier phase, which is usually symbolized by "ϕ". This observable carrier phase represents the frequency difference between the satellite carrier and that generated in the receiver, a so-called "beat" phase difference. This phase measurement observation is shown in Eq.(1) for the observable carrier phase.

$$\begin{aligned}\phi_\alpha^j(t) =&\rho_\alpha^j(t) - \lambda N_\alpha^j + \phi_{\text{initial}}^j + c\cdot d_{\text{ion}}^j\\ &- c\cdot d_{\text{trop}}^j + \varepsilon(\phi) - c\cdot(dt^j + dT_\alpha)\end{aligned} \tag{1}$$

In Eq.(1), $\phi_\alpha^j(t)$ is the carrier phase variation measured between the antenna α and satellite j (in meters) at time t (starting from the receiver's satellite acquisition instant), $\rho_\alpha^j(t)$ is the geometric range (distance) from antenna α to satellite j at time t, λ is the wavelength for the L1 GPS frequency (0.1904 meters), N_α^j is the integer carrier phase cycle ambiguity between antenna α and satellite j, ϕ_{initial}^j is the carrier phase at the moment of transmission from satellite j, c is the propagation speed of electromagnetic waves in space, d^j_{ion} is the ionospheric signal delay for satellite j, d^j_{trop} is the tropospheric signal delay for satellite j, $\varepsilon(\phi)$ is the carrier phase measurement error due to receiver noise and multipath error (up to 5cm), dt^j is the satellite j clock error, and dT_α is the receiver α error.

Two receivers are needed for this technique. One is a known reference point (the reference receiver) and the other is a "remote" or "rover" receiver (the user's receiver). To eliminate clock errors in the satellite, the "single difference" between phase measurements of the reference and remote receivers can be used, as shown in Fig.2. Furthermore, if the resultant single differences between satellites are again differentiated, the result is called the "double difference" (Eqs.(2) and (3)). The double difference is mostly used in carrier phase tracking and the receiver clock and atmospheric errors can be eliminated, but this approach reduces the influence of atmospheric errors only over very short baselines. More details of the double difference solution algorithm have been previously introduced[12]. If two double differences are performed over two different epochs, it is referred to as a triple difference. There are problems in carrier phase tracking for higher precision such as integer ambiguity and cycle slips.

$$\begin{aligned}\Delta\phi^j_{\beta\alpha}(t) =& \Delta\rho^j_{\beta\alpha}(t) - \lambda\Delta N^j_{\beta\alpha} - c\Delta dT_{\beta\alpha} \\ & - \Delta c\cdot d^j_{ion\beta\alpha} + \Delta c\cdot d^j_{trop\beta\alpha} + \varepsilon(\Delta\phi_{\beta\alpha})\end{aligned} \tag{2}$$

Δ represents the difference between receivers.

$$\nabla\Delta\phi^{ji}_{\beta\alpha} = \nabla\Delta\rho^{ji}_{\beta\alpha} + \lambda\nabla\Delta N^{ji}_{\beta\alpha} + \varepsilon(\nabla\Delta\phi_{\beta\alpha}) \tag{3}$$

∇ represents the difference between satellites.

As mentioned in Section II, GPS receivers using carrier phase tracking technology can be much more accurate but high-precision GPS receivers are either used for the military or are too expensive. Low-cost civilian GPS receivers always use code pseudo-range tracking and their accuracy is only about 5m[5] so they cannot meet the needs of high-precision location services such as automotive application services. Therefore, we focused on the use of a code pseudo-range GPS receiver in this study in order to gain more accurate relative location information for automotive application services.

IV. Proposed Relative Positioning Algorithm

Differential positioning technology can be very precise. However, it has some disadvantages including service area limitation, availability limitation, and base station dependency, which is its biggest disadvantage. The system is heavily dependent on the base stations and the base stations can decide whether or not they want to share data. Therefore, the system is not very trustworthy. Thus, we consider changing the base station to a normal vehicle, as shown in Fig.3.

There is another disadvantage to code tracking differential positioning technology. The base station calculates a correction value specific to its own environment but the user's environment may be different from that of the base station. In addition, the user may receive information from a different satellite set than the base station, as shown in Fig.4. Therefore, even if the user uses the correction value that was calculated by the base station, its results may still not be very accurate. Hence, we must consider whether to select the same satellite information for two neighboring vehicles to calculate their relative position.

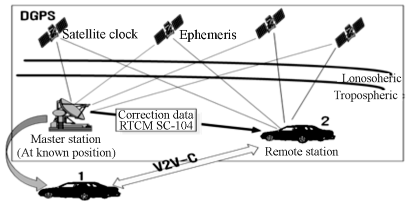


Fig. 3. Concept of the proposed algorithm

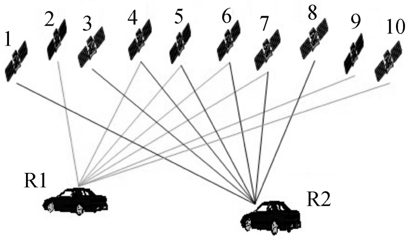


Fig. 4. Receivers obtaining information from satellites

As mentioned in Section III, the reference or base station receiver calculates the pseudo-range correction and transmits it to the remote or rover receiver. Then, the user's receivers can correct the raw pseudo-ranges originally observed and the accuracy of positioning will be improved. When the reference or base station calculates the pseudo-range correction, it should use the absolute point positioning method to calculate its position. As shown in Fig.4, R1 should do this work. If we consider each kind of error that occurs during the data transmission period from the satellite to R1, we can determine the real distance between two vehicles using Eq.(4). The parameter ρ_i can be calculated using Eq.(5) and the parameter ρ_{iT} can be calculated using Eq.(6).

$$\rho_i = \rho_{iT} + \Delta D_i - c(\Delta b_i - b_{ut}) + c(\Delta T_i + \Delta I_i + v_i + \Delta V_i) \tag{4}$$

Here, ΔD_i represents the effect of the satellite position error on the range, Δb_i is the satellite clock error, b_{ut} is the user clock error, ΔT_i is the tropospheric delay error, ΔI_i is the ionospheric error, v_i is the receiver measurement noise error, and ΔV_i is the relativistic time correction.

$$\rho_i = c(t_u - t_{si}) \tag{5}$$

In Eq.(5), ρ_{it} denotes the distance between the user and the satellite and is often referred to as the true value of the pseudo-range from the user to the satellite, c is the speed of light, t_u is the time at which the receiver receives the signal and is referred to as the true time of reception, and t_{si} is the time at which each satellite sends a signal and is referred to as the true time of transmission from the satellite.

$$\rho_{iT} = \sqrt{(x_i - x_u)^2 + (y_i - y_u)^2 + (z_i - z_u)^2} \tag{6}$$

Here, (x_i, y_i, z_i) denotes the satellite position and (x_0, y_0, z_0) is the user position.

If we consider the sub-equation $\Delta D_i - c(\Delta b_i - b_{ut}) + c(\Delta T_i + \Delta I_i + v_i + \Delta V_i)$ as one parameter denoted as the TE (total error) and obtain position information from four satellites such as satellites 4, 5, 6, and 7 in Fig.4, R1 can calculate its x, y, and z values with the addition of TE. Then, the TE will be used as the pseudo-range correction and will be transmitted to R2.

In our proposed algorithm, the user and its neighbor will share the tracked satellite numbers, their calculated positions, the time, and some other information. Then, they will select the same satellite information to calculate their absolute position, as shown in Fig.4. R1 can receive information from satellites 2, 4, 5, 6, 7, 9, and 10, and R2 can receive information from satellites 1, 3, 4, 5, 6, 7, and 8. Then, they will select the information from the same satellites (4, 5, 6, and 7) to calculate their location. In this way, they will have the same satellite error so the parameter ΔD_i in the TE expression will be the same. The other parameters in the TE equation are generated by the data transmission between R1 and the satellites. If R2 is very close to R1, they maintain nearly the same status so that those errors will also be the same under ideal conditions.

However, in real conditions, the error caused by the data transmission between R1 and R2 should also be considered. Most automotive application services are provided while the vehicle is moving but if the data transmit time is too long, then R1 and R2 will be in two different environments. In order to consider the error caused by data transmission, the WAVE protocol was used to simulate the vehicle network environment on Qualnet[13].

The WAVE protocol uses the 10 MHz frequency and divides it into seven channels from CH 172 to CH 184. Among these channels, there is one control channel and six service channels. And SCH 172 is the most suitable channel for data transmission between R1 and R2. From the simulation on Qualnet, if the transmit data rate is 6 Mbps, each vehicle's radio range is up to 850m, and the end-to-end delay will remain 4.5ms.[13]

In the proposed algorithm, only the near node can be selected as the reference and if the distance between the two nodes is larger than 850m, they may be in different environments such that only one-hop communication is considered when calculating the time delay caused by the data communication.

For the end-to-end delay, in the highway environment, the maximum speed is 100km/h so we can assume that R1 and R2's maximum relative speed is 200km/h and their initial distance is 0m. After 4.5ms, two vehicles will be a maximum of 0.25m apart. Since each vehicle's body is longer than 1m, we can still assume that the two vehicles stay in the same environment and when calculating their relative position, we can remove this error by forecasting it based on the vehicles' relative speed.

In our proposed algorithm, although selection of the satellite information with the same satellite number would reduce the amount of satellite information, which may cause a bigger error in determining the absolute position, the two users are assumed to have the same total error in this algorithm. As shown in Fig.5, the two vehicles moving along the solid and dotted lines, which are initially parallel, become curved after the vehicles' real-time absolute positions are determined. In the ideal situation, these curves will remain parallel to each other and if we subtract one from the other, we can achieve more accurate relative position information in real-time.

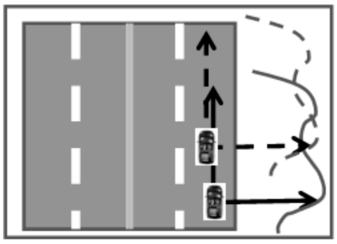


Fig. 5. Relative position concept

V. Tests and Results

In order to demonstrate the value of our algorithm, we used two types of GPS receivers: GPS 641 and AKN-1M. We connected them to a computer, as shown in Fig.6, and after collecting enough data, we used MATLAB for the analysis. The specifications of the two GPS receivers are shown in Fig.7.

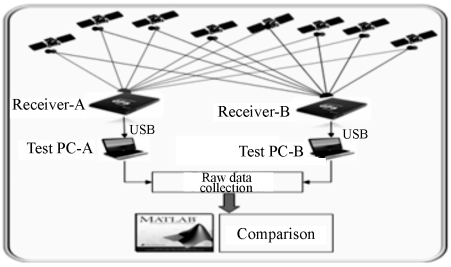


Fig. 6. Test concept

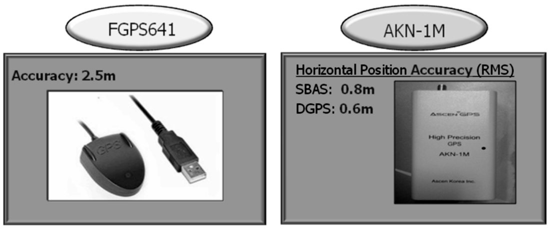


Fig. 7. GPS module specifications

All tests were conducted at our school's playground and included both stationary and dynamic environments. First, we conducted a stationary test. We put two GPS 641 GPS receivers and two AKN-1M GPS receivers in two places 4m apart and collected satellite information for 30 minutes.

As shown in Fig.4, the communicated satellite numbers of the two GPS receivers were different in our tests and they continuously changed. For example, at 02h:11m:58s, one GPS receiver could receive data from satellites 10, 02, 17, and 04 and the other could receive data from satellites 13, 02, 04, 10, and 17. Most of the satellites are the same such that both GPS receivers can use the data from satellites 10, 02, 17, and 04 to calculate their relative position. But at 12h:21m:06s, one GPS receiver could receive data from satellites 23, 30, 16, 31, 29, 06, 13, 21, 03, and 19 and the other one could receive data from satellites 30, 06, 31, and 16. Therefore, both GPS receivers can only use the data from satellites 30, 06, 31, and 16 to calculate their relative position.

After collecting enough data, we compared the results obtained with and without our proposed algorithm. The results obtained without the algorithm are termed "results of total data", while the results obtained using the algorithm are termed "results of same satellite data". Two parameters were used to evaluate this algorithm's performance: the two GPS receivers' average error and their variance. The test results are shown in Table 1.

Table 1. Average errors (m) and variances of the two stationary tests

Distance (m) GPS model		GPS 641		AKN-1M	
		Average errors (m)	Variances	Average errors (m)	Variances
4	Results of total data	0.367	0.217	0.048	0.092
	Results of same satellite data	0.350	0.181	0.047	0.089
10	Results of total data	0.126	0.152	0.062	0.041
	Results of same satellite data	0.035	0.086	0.019	0.037

In Table 1, it is evident that the average errors of the tests improved by an average of 25.2% due to our proposed algorithm. It is also apparent in Table 2 that almost all of these tests' variances improved by an average of approximately 21.7%. These results prove that our proposed algorithm works well in a stationary environment.

We then used two different GPS receivers to perform the same test in order to assess the versatility of our algorithm. The results are shown in Table 2.

Table 2. Average errors (m) and variances of the other two stationary tests

Distance (m) GPS model		GPS 641 & AKN-1M	
		Average errors (m)	Variances
4	Results of total data	1.776	3.953
	Results of same satellite data	2.021	5.072
10	Results of total data	0.722	0.893
	Results of same satellite data	0.843	1.068

The modules of the two GPS receivers are different, which will lead to error, and the difference in their transition error modulation methods will lead to a transition correction value difference. If we use our proposed algorithm in this situation, less satellite information will be used to calculate the receivers' absolute positions such that the results generated using our proposed algorithm will have greater error in the relative position determination. This is a limitation of the proposed method where the same equipment must be used.

Taking into account the fact that the ultimate purpose of this proposed algorithm is to be applied in the automotive environment, we performed a dynamic status test on the road using two identical GPS modules. The two GPS receivers were fixed on the car's right windows 1 m apart, as shown in Fig.8. The car was driven at 20km/h, 40km/h, and 60km/h, and the two GPS receivers collected information while the car was driven. The data was then analyzed in the same way as in the stationary environment.

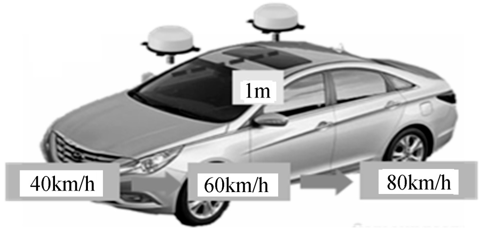


Fig. 8. Automotive environment test

Table 3. Average errors (m) and variances of the three dynamic tests

Velocity (km/h) GPS model		GPS 641		AKN-1M	
		Average errors (m)	Variances	Average errors (m)	Variances
20	Results of total data	1.515	0.578	1.075	0.086
	Results of same satellite data	1.075	0.462	1.062	0.060
40	Results of total data	3.147	6.518	0.981	0.171
	Results of same satellite data	2.412	2.396	1.070	0.151
60	Results of Total Data	5.741	17.239	1.986	3.543
	Results of same satellite tata	3.600	7.384	2.004	2.264

It is evident in Table 3 that all of the average errors and variances were reduced when using our algorithm. The average error and variance were improved by approximately 22.3% and 54.8%, respectively. These findings prove that our proposed algorithm can be implemented in the vehicle environment resulting in very good performance.

VI. Conclusions and Future Work

We proposed a new method to calculate the relative position with higher accuracy using low-cost code tracking GPS receivers. So far, we only calculated the relative distance between two GPS satellite receivers but for automobile services implementation, each vehicle must know the direction vector with respect to other vehicles. Therefore, based on this work, we need to determine the directions of each neighbor relative to the vehicle in addition to their relative position vector.

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XU Shenglei received his M.S. degree from Hanyang University, Korea, in 2009. He is currently a Ph.D. Student of Hanyang University, His research interests are Ad-hoc routing protocol development and simulation in vehicle to vehicle communication, communication standardization and protocol development in ITS/Telematics and positioning technology. (Email: xushenglei866@hotmail.com)

Sangsun LEE(Corresponding author) received his B.S. degree and M.S. degree from Hanyang Univeristy, Korea, in 1978 and 1983, and received his Ph.D. degree from University of Florida, USA, in 1990, and since 1993, he has been a professor of College of Information & Communications Department of Electronics Computer Engineering in Hanyang University. From 2002, he has become an Internal Commissary of Korean Standards Association ISO TC204 WG16, and has become a member of Technique Section of Ministry of Knowledge Economy Department, Car Telematics Forum from 2005. Also from 2005, he has become the Chairman of ITS Korean Public Transit Information Management and Communications Research Committee, and then from the next year 2006, he has become the Chairman of TTAPG310 ITS/Telematics Section, and also has become the Chairman of Korean Information and Communications Society ITS/Telematics Research Committee.