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Application of the Vehicle Navigation via GPS Carrier Phase

GUO-SHING HUANG
Department of Electronic Engineering,
National Chin-Yi Institute of Technology
35, Lane 215, Chung-Shan Rd., Sec. 1, Taiping, Taichung, 411,
TAIWAN, ROC
http://www.ncit.edu.tw

Abstract: - Today, Global Position System (GPS) is extensively employed in navigation and survey systems. Because the GPS can provide navigation data such as position, velocity, attitude and heading of vehicles, its contributions are numerous not only in national defense and military but also in commercial fields. However, GPS is usually used to provide absolute position information. In attitude problems, the inertial navigation system (INS) is usually employed in navigator to solve its attitude. In this paper, the main purpose is to perform the real-time kinematic GPS and the attitude determination using the GPS carrier phase observation. A navigation vehicle has been designed in order to test and verify the accurate performance of the system by the proposed real-time kinematic GPS and attitude determination algorithms. Through some experiments, the proposed approaches satisfy our requirements via the test.

Key-Words: Real-time Kinematic GPS, Attitude Determination, Inertial Navigation System, Entended Kalman Filter

1 Introduction

Recently, some research methods and theorems of the navigation in autonomous mobile robot have been developed. The most often used ones for the long-distance navigation of vehicles certainly has been Inertial Navigation System (INS). The INS is a stand-alone, real-time guidance system, which has a high immunity of environmental noise and does not require data transmission. Due to the accumulation of errors for the INS, however, the positioning data will tend to diverge. Such a disadvantage blocks the application of INS in the long-time navigation when no extra correction is made. In order to improve this shortcoming, some research papers propose a combination INS with GPS to make the error revision [1]. The integrated system uses the precise GPS data to reduce system error accumulation of the INS system, and compensates the shortage GPS data with the high data rate of INS. However, the capability of dealing with the attitude problem is not yet fully developed in such an integration system. Attitude determination using GPS receivers has increasingly become more important in some fields such as the navigation of aircraft, ships, and automobiles. There is a continuous demand for more information regarding the object in question, in addition to its position, in order to assess issues, such as safety in fly-by-wire systems for example[2]. The key of the real-time kinematic GPS and the attitude determination is to find the correct carrier phase integer ambiguity values. An evaluation of existing ambiguity resolutions on the fly techniques can be found in [3]. The real integer ambiguity, position, velocity, and acceleration of a moving platform can be estimated using the Kalman filter technique [4] or the sequential least squares method [5]. In order to have a fast response and high accuracy, the study in [6] proposed a method, based on a multiple model adaptive Kalman filter approach, to obtain the real-time kinematic carrier phase cycle ambiguity resolution. . The extended Kalman filter approach was presented using accumulated carrier phase measurements from a P-code GPS receiver and an inertial measurement unit to produce well-focused synthetic aperture radar imagery in real time [7]. The Kalman filter technique is very popular in the integrated navigation systems [8-11].

This paper aims at setting up a real time kinematic GPS positioning and attitude determination algorithm using a single frequency L1 carrier phase double difference measurement equation, and the extended Kalman filter method to resolve the real-time positioning and the attitude of the navigator. Section 2 describes a theoretical derivation of KGPS positioning. Section 3 demonstrates how by using the attitude determination algorithm the attitude of navigator can be found. In Section 4, the extended Kalman filter approach is explained. Experimental results and discussion are described in Section 5. Section 6 presents some conclusions.

2 KGPS Positioning Theorem

The conventional DGPS positioning technique is concerned with transmitting the observed GPS data, corrected with respect to all the GPS satellites at the base station, to the user's mobile station for reference via wireless modems or radio beacons. The user station updates its position using these correction parameters from the reference station. However, the accuracy of this type of positioning can only be achieved at meter level. Since the more sophisticated process of accuracy improvement is almost always performed by the base station, the user station only plays a role in receiving more accurate corrections and updating position in more precise way. This paper proposes a new concept of KGPS positioning technique in which the base station transmits all GPS observation data to the user station in real time via wireless modems. Other matters are done by the user to perform the resolution of the unit vector of a reference point with respect to each individual GPS satellite, the double difference carrier phase integer ambiguity, and a high-precision fixed solution. This process is performed in real time and achieves a high accuracy at decimeter level. In the sequel we derive the equation of KGPS positioning from the GPS satellite's messages, observed by the user station, and show how the base station measurement GPS navigation messages are transmitted via dual wireless modems.

$$\Phi_{mn}^{ij}(t) = \frac{f}{c}\left[\rho_n^j - \rho_m^j\right] - \frac{f}{c}\left[\rho_n^i - \rho_m^i\right] + N_{nn}^{ij} + \frac{f}{c}\left[\dot{\rho}_n^j(t)dt_n - \dot{\rho}_m^j(t)dt_m\right]$$
$$- \frac{f}{c}\left[\dot{\rho}_n^i(t)dt_n - \dot{\rho}_m^i(t)dt_m\right] + I_{mn,\phi}^{ij}(t) + \frac{f}{c}T_{mn}^{ij}(t) + d_{mn,\phi}^{ij}(t) + \varepsilon_{mn,\phi}^{ij} \tag{2.1}$$

where

$\rho_m^i(t) = \sqrt{\left(x^i - x_m\right)^2 + \left(y^i - y_m\right)^2 + \left(z^i - z_m\right)^2}$ denotes the distance between based station *m* and *i*-th GPS satellite, and

$\rho_n^i(t) = \sqrt{\left(x^i - x_n\right)^2 + \left(y^i - y_n\right)^2 + \left(z^i - z_n\right)^2}$ is the distance between mobile station *n* and *i*-th GPS satellite. For the sake of simplifying the derivation of KGPS theorem, we introduce the following notations:

$\rho_{mn}^{ij}(t) = \rho_{mn}^j(t) - \rho_{mn}^i(t)$ denotes the double difference of distance for the based station *m* and the mobile station *n* observed separately with respect to i-th and *j*-th GPS satellites.

$I_{mn,\phi}^{ij}(t) = I_{mn,\phi}^j(t) - I_{mn,\phi}^i$ is the double difference of ionospheric delay for the base station *m* and the mobile station *n* observed separately with respect to *i*-th and *j*-th GPS satellites.

$T_{mn}^{ij}(t) = T_{mn}^j(t) - T_{mn}^i(t)$ represents the double difference of tropospheric delay for the based station *m* and the mobile station *n* observe separately with respect to *i*-th and *j*-th GPS satellites.

$\varepsilon_{mn,\phi}^{ij} = \varepsilon_{mn,\phi}^j - \varepsilon_{mn,\phi}^i$ is defined as the double difference of the random carrier phase measurement noise for the based station *m* and the mobile station *n* observe separately with respect to *i*-th and *j*-th GPS satellites.

$d_{mn,\phi}^{ij}(t) = d_{mn,\phi}^j(t) - d_{mn,\phi}^i(t)$ stands for the double difference of the multipath for the based station *m* and the mobile station *n* observe separately with respect to *i*-th and *j*-th GPS satellites.

Moreover, assuming the hardware delay of GPS receiver and satellites, the multipath effect, and the measurement noise to be negligible, Eq.(2.1) can be rewritten as

$$\Phi_{mn}^{ij}(t)=\frac{f}{c}[\rho_{mn}^{j}(t)-\rho_{mn}^{i}(t)]+N_{mn}^{ij}$$

$$=\frac{f}{c}\left[\frac{S_j^{[e]}}{\left\|S_j^{[e]}\right\|}-\frac{S_i^{[e]}}{\left\|S_i^{[e]}\right\|}\right](X_n-X_m)+N_{mn}^{ij}(t)$$

Where $\frac{S_j^{[e]}}{\left\|S_j^{[e]}\right\|}$ is the unit vector of reference point pointing to *j*-th GPS satellite, and $\frac{S_i^{[e]}}{\left\|S_i^{[e]}\right\|}$ is the unit vector of reference point pointing to *i*-th GPS satellite. $X_n=\left[x_n \quad y_n \quad z_n\right]$ be the position of the mobile station, and $X_m=\left[x_m \quad y_m \quad z_m\right]$ be the position of the based station.

Assume that the position X_m of based station is known, the double difference measurement carrier phase is observed, two variables of this government equation are unknown that are the integer ambiguity N_{mn}^{ij} and the position of client station X_n

3 Attitude Determination Algorithm

The double difference carrier phase measurements can be modeled with the following equations:

$$\Phi_{mn}^{ij}(t)=\frac{f}{c}\left[\frac{S_j^{[e]}}{\left\|S_j^{[e]}\right\|}-\frac{S_i^{[e]}}{\left\|S_i^{[e]}\right\|}\right]\left(X_n-X_m\right)+N_{mn}^{ij}(t)$$

$$=\frac{f}{c}\left[\frac{S_j^{[e]}}{\left\|S_j^{[e]}\right\|}-\frac{S_i^{[e]}}{\left\|S_i^{[e]}\right\|}\right]\left(C_b^e a_n^{[b]}-C_b^e a_m^{[b]}\right)+N_{mn}^{ij}(t)$$

$$=\frac{f}{c}\left[\frac{S_j^{[e]}}{\left\|S_j^{[e]}\right\|}-\frac{S_i^{[e]}}{\left\|S_i^{[e]}\right\|}\right]C_b^e(a_n^{[b]}-a_m^{[b]})+N_{mn}^{ij}(t)$$

The 3×3 attitude matrix C_e^b , transforms vector from the Earth-Centered Earth-Fixed *e*-frame to the Body-Fixed *b*-frame. In terms of matrix rotation,

$$C_e^b(t)=C_m^b(t)C_e^m(t)=R_2(\alpha)R_1(\theta)R_3(\psi)R_1(\frac{\pi}{2}-\phi)R_3(\frac{\pi}{2}+\lambda)$$

Assume that there are two antennas located at $a_m^{[b]}=\begin{bmatrix}0\\0\\0\end{bmatrix}$ and $a_n^{[b]}=\begin{bmatrix}0\\L_{12}\\0\end{bmatrix}$, respectively. The variable L_{12} is the baseline length between the two antennas. The double difference equation can then be simplified as

$$\Phi_{mn}^{ij}=\frac{df}{c}[c\theta s\psi s\lambda-c\theta c\psi s\phi c\lambda+s\theta c\phi c\lambda$$

$$-c\theta s\psi c\lambda-c\theta c\psi s\phi s\lambda+s\theta c\phi s\lambda \quad c\theta c\psi c\phi+s\theta s\phi]\times\left[\frac{s_i^{[e]}}{\left\|s_i^{[e]}\right\|}-\frac{s_j^{[e]}}{\left\|s_j^{[e]}\right\|}\right]+N_{mn}^{ij}$$

(3.1)

In the above, the variables λ and ϕ are obtained from the GPS positioning data, $s_i^{[e]}$ and $s_j^{[e]}$ are obtained from the satellite ephemeris data, and Φ_{mn}^{ij} is the double difference of the GPS carrier phase measurements. The unknowns are the azimuth angle ψ , the roll angle θ and the integer ambiguity N_{mn}^{ij} . Let

$$P'(k)=\frac{df}{c}\left[\sin\lambda \quad -\cos\lambda \quad 0\right]\left[\frac{s_i^{[e]}}{\left\|s_i^{[e]}\right\|}-\frac{s_j^{[e]}}{\left\|s_j^{[e]}\right\|}\right],$$

$$Q'(k)=\frac{df}{c}\left[-\sin\phi\cos\lambda \quad -\sin\phi\sin\lambda \quad \cos\phi\right]\left[\frac{s_i^{[e]}}{\left\|s_i^{[e]}\right\|}-\frac{s_j^{[e]}}{\left\|s_j^{[e]}\right\|}\right]$$

$$R'(k)=\frac{df}{c}\left[\cos\lambda \quad \cos\phi\sin\lambda \quad \sin\phi\right]\left[\frac{s_i^{[e]}}{\left\|s_i^{[e]}\right\|}-\frac{s_j^{[e]}}{\left\|s_j^{[e]}\right\|}\right].$$

Then, (3.1) can be rearranged as

$$\Phi_{mn}^{ij}(k)=P'(k)\cos\theta\sin\psi+Q'(k)\cos\theta\cos\psi+R'(k)\sin\theta+N_{mn}^{ij}$$

4 Extended Kalman Filter

We use the EKF method separately to estimate the point of location and attitude of the vehicle.

We define the observation vector of $z_1 = \left[\Phi_{mn}^{12}\Phi_{mn}^{13}\Phi_{mn}^{14}\right]^T$ and the state vector x_1,

$$x_1 = \begin{bmatrix} x_n & y_{\mathrm{n}} & z_n & N_{mn}^{12} & N_{mn}^{13} & N_{mn}^{14} \end{bmatrix}^T$$

$$H_{x_1} = \left[\begin{matrix} \dfrac{s_{1x}^{[e]}}{\left\|s_{1x}^{[e]}\right\|} - \dfrac{s_{2x}^{[e]}}{\left\|s_{2x}^{[e]}\right\|} & \dfrac{s_{y1}^{[e]}}{\left\|s_{1y}^{[e]}\right\|} - \dfrac{s_{2y}^{[e]}}{\left\|s_{2y}^{[e]}\right\|} & \dfrac{s_{z1}^{[e]}}{\left\|s_{1z}^{[e]}\right\|} - \dfrac{s_{2z}^{[e]}}{\left\|s_{2z}^{[e]}\right\|} \\ \dfrac{s_{x1}^{[e]}}{\left\|s_{1x}^{[e]}\right\|} - \dfrac{s_{2x}^{[e]}}{\left\|s_{2x}^{[e]}\right\|} & \dfrac{s_{1y}^{[e]}}{\left\|s_{1y}^{[e]}\right\|} - \dfrac{s_{2y}^{[e]}}{\left\|s_{2y}^{[e]}\right\|} & \dfrac{s_{1z}^{[e]}}{\left\|s_{1z}^{[e]}\right\|} - \dfrac{s_{2z}^{[e]}}{\left\|s_{2z}^{[e]}\right\|} \\ \dfrac{s_{1x}^{[e]}}{\left\|s_{1x}^{[e]}\right\|} - \dfrac{s_{2x}^{[e]}}{\left\|s_{2x}^{[e]}\right\|} & \dfrac{s_{1y}^{[e]}}{\left\|s_{1y}^{[e]}\right\|} - \dfrac{s_{2y}^{[e]}}{\left\|s_{2y}^{[e]}\right\|} & \dfrac{s_{1z}^{[e]}}{\left\|s_{1z}^{[e]}\right\|} - \dfrac{s_{2z}^{[e]}}{\left\|s_{2z}^{[e]}\right\|} \end{matrix}\right.$$

$$\left.\begin{matrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{matrix}\right]$$

and define the observation vector of attitude determination $z_2 = \left[\Phi_{mo}^{12}\Phi_{mo}^{13}\Phi_{mo}^{14}\right]^T$ and the state vector $x_2 = \begin{bmatrix} \theta & \psi & N_{mo}^{13} & N_{mo}^{13} & N_{mo}^{14} \end{bmatrix}^T$ and that $h(x_2(k))$ is a nonlinear matrix of the state x_2.

Linearization of $h(x_2(k))$ gives

$$H_{x_2} = \frac{\partial h(x_2)}{\partial x_2} =$$

$$\left[\begin{matrix} -P_{mn}^{12}s\theta_{mn}s\psi_{mn} + Q_{mn}^{12}s\theta_{mn}c\psi_{mn} + R_{mn}^{12}c\theta_{mn} & P_{mn}^{12}c\theta_{mn}c\psi_{mn} - Q_{mn}^{12}c\theta_{mn}s\psi_{mn} \\ -P_{mn}^{13}s\theta_{mn}s\psi_{mn} + Q_{mn}^{13}s\theta_{mn}c\psi_{mn} + R_{mn}^{13}c\theta_{mn} & P_{mn}^{13}c\theta_{mn}c\psi_{mn} - Q_{mn}^{13}c\theta_{mn}s\psi_{mn} \\ \vdots & \vdots \\ -P_{mn}^{1n_s}s\theta_{mn}s\psi_{mn} + Q_{mn}^{1n_s}s\theta_{mn}c\psi_{mn} + R_{mn}^{1n_s}c\theta_{mn} & P_{mn}^{1n_s}c\theta_{mn}c\psi_{mn} - Q_{mn}^{1n_s}c\theta_{mn}s\psi_{mn} \\ 0 & 0 \\ 0 & 0 \\ \vdots & \vdots \\ 0 & 0 \end{matrix}\right.$$

$$\begin{matrix} 0 & 0 \\ 0 & 0 \\ \vdots & \vdots \\ 0 & 0 \\ -P_{mo}^{12}s\theta_{mo}s\psi_{mo} + Q_{mo}^{12}s\theta_{mo}c\psi_{mo} + R_{mo}^{12}c\theta_{mo} & P_{mo}^{12}c\theta_{mo}c\psi_{mo} - Q_{mo}^{12}c\theta_{mo}s\psi_{mo} \\ -P_{mo}^{13}s\theta_{mo}s\psi_{mo} + Q_{mo}^{13}s\theta_{mo}c\psi_{mo} + R_{mo}^{12}c\theta_{mo} & P_{mo}^{13}c\theta_{mo}c\psi_{mo} - Q_{mo}^{13}c\theta_{mo}s\psi_{mo} \\ \vdots & \vdots \\ -P_{mo}^{1n_s}s\theta_{mo}s\psi_{mo} + Q_{mo}^{1n_s}s\theta_{mo}c\psi_{mo} + R_{mo}^{1n_s}c\theta_{mo} & P_{mo}^{1n_s}c\theta_{mo}c\psi_{mo} - Q_{mo}^{1n_s}c\theta_{mo}s\psi_{mo} \end{matrix}$$

$$\left.\begin{matrix} 1 & & & & & & \\ & 1 & & & & & \\ & & \ddots & & 0 & & \\ & & & 1 & & & \\ & & & & 1 & & \\ & & 0 & & 1 & & \\ & & & & & \ddots & \\ & & & & & & 1 \end{matrix}\right]$$

The state equation and the measurement equation of the system are described by

$$x(k) = F(k)x(k-1) + \omega(k-1)$$

$$z(k) = h(x(k)) + v(k)$$

where $\omega(k)$ is the white noise process and $v(k)$ the white measurement noise process.

5 Experimental Results and Discussion

An experiment was set up to access these two proposed system. A navigation vehicle has been designed in order to test and verify the accurate performance of the system by the proposed real-time kinematic GPS and attitude algorithms as shown in Figure 1. The navigation vehicle according to its function can be divided into several parts. The driving part consists of two DC motors and the power source of the navigation vehicle, which are controlled by a DSP 2407A as shown in Figure 2. The task of the DSP is to generate PWM (Pulse Width Modulation) signals for DC motors according to the measurements of the odometer and the given desired values, which are transferred from a host computer to the vehicle via the radio modem. For internal communication, a proprietary radio module is used based on a 802.11g wireless. The navigator installed two GPS receivers which were used to obtain the absolute position and attitude estimation of this navigation vehicle. Two GPS antennas were mounted at the ends of a 1-meter long baseline as shown in Figure 3, which provided the measurements of the vehicular attitude. Another antenna was put on the base station. The base station took the responsibility to transmit all GPS observation data from the GPS receiver of the reference station to the navigation vehicle in real time via the wireless modem. On the other side, the navigation vehicle had to execute the KGPS algorithms such as the resolution of the unit vector of a reference point with respect to the individual GPS satellite. Figure 4 illustrates the concept of the whole experimental system.

In order to avoid the interference and reflection from the environments, the athletic field of our campus was chosen for the place of the experiment. In this environment, the navigator could easily observe the GPS satellites to avoid a shield.

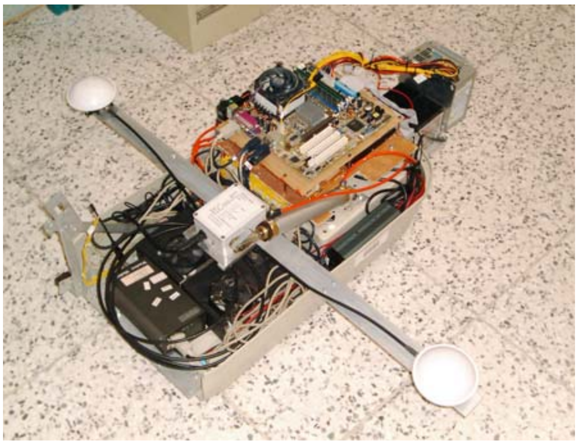

Fig.1 Picture of the navigation vehicle

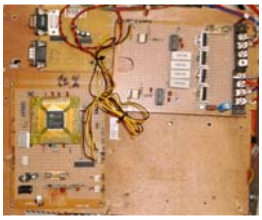

Fig.2 DSP card motion control

Fig.3 GPS receiver

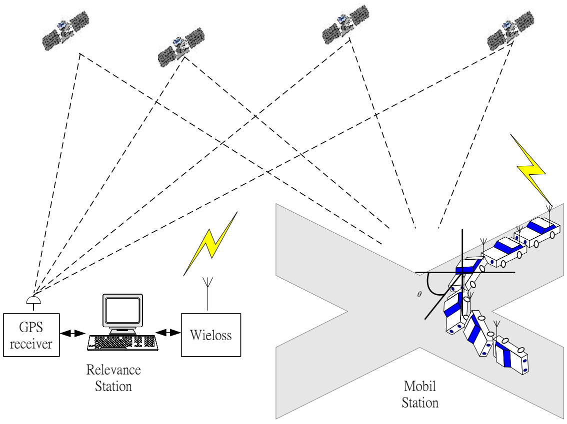

Fig.4 Schematics of the experimental system

With respect to the point of view, we can relatively obtain a high precision positioning. The elliptical runway on the field has marked the line of runway, therefore the navigator could run along the line of runway around in one circle and drew complete the entire route. It is easier to compare the line of the runway of the navigator with the marked line of the runway. The whole experiment consisted of setting one of the GPS receiver's antenna onto a highly accurate test point as a base station, the other mounted on a navigator as a moving station, and then set up the GPS receiver and the wireless transmitter/receiver modem, respectively. Utilizing the wireless modem, we transmitted the measurement data and a high precision measurement position of the base station to the user station. The algorithm then started the computer programs to resolve the high-accuracy position and attitude estimation using the extended Kalman filter approach. We selected the engineering building as the base station, drove the navigation vehicle along the line of the runway. The experimental results are drawn and shown in Figure 5. Figure 6 shows the results of the attitude determination using EKF and the comparison with compass. The attitude heading angle is shown about 360 degrees from a starting point to the point where the navigation vehicle stopped.

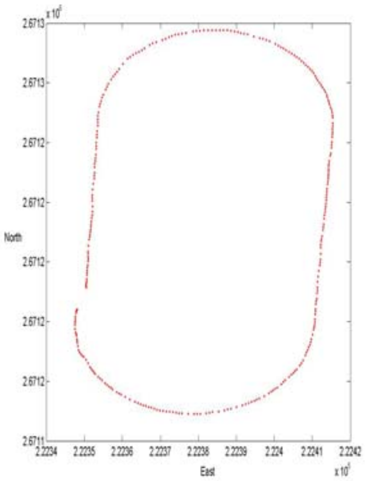

Fig.5 Trajectories of the moving navigation vehicle with the extended Kalman filter technique and GPS receiver position data

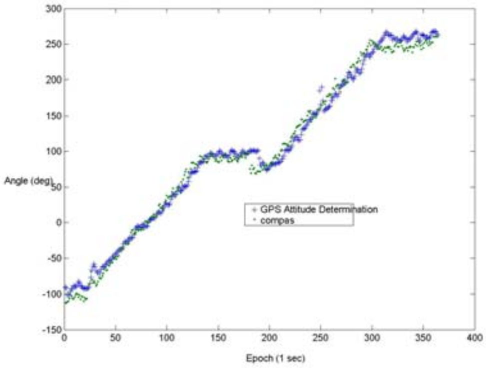

Fig.6 The attitude of navigator using EKF approach

6 Conclusions

In this paper, the main purpose has been to resolve the real-time kinematic GPS and attitude determination of the navigator using the GPS carrier phase observation. The aim was to design a navigator—an automobile and verify these two functions. A kinematic GPS positioning and attitude determination technique using the extended Kalaman filter approach with three GPS receivers performing carrier phase observation has been developed and describes. Through the experimental results, the kinematic GPS performed a real-time position estimation with accuracy up to decimeter level, and a real-time attitude estimation for the navigator could be obtained by using the attitude determination algorithms. The proposed approaches satisfy our requirements via the test.

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