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A Low-cost GPS / INS Integrated Vehicle Heading Angle Measurement System

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Abstract. GPS can provide continuous heading information, but the accuracy is easily affected by the velocity and shelter from buildings or trees. For vehicle systems, we propose a low-cost heading angle update algorithm. Based on the GPS/INS integrated navigation kalman filter, we add the GPS heading angle to the measurement vector, and establish its error model. The experiment results show that this algorithm can effectively improve the accuracy of GPS heading angle.

Key words: Heading angle; GPS/SINS integrated navigation system; kalman filter.

INTRODUCTION

The Heading angle is an important parameter of the vehicle navigation system, which directly determines the navigation accuracy. In the past, most of us use INS for vehicle attitude measurement. However, errors in the INS output grow in an unbounded manner owing to its dead-reckoning nature. High accuracy inertial navigation requires costly inertial sensors which limits its use in low-cost applications. MEMS sensors provide low-cost INS solution but require constant external aiding to keep navigation errors bounded [1].

Multi-antenna GPS is another important tool for vehicle attitude measurement, but this type of receiver is expensive and difficult to popularize in the consumer market. Aiming at the above problems, this paper designs a real-time vehicle heading angle measurement system with MEMS inertial sensor and low-cost GPS receiver to obtain long-term stable vehicle heading angle.

SYSTEM DESIGN

GPS heading angle

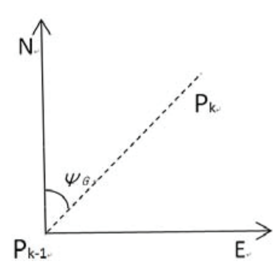

FIG.1 Calculation principle of GPS heading angle

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GPS heading angle is the course angle in the NMEA183 protocol, which can be directly parsed from the $GPRMC. Course angle can be utilized as one measurement for estimation design, together with the yaw rate from gyroscope [2]. The calculation principle of the course angle is shown in fig. 1. The course angle is calculated as follows,

$$\psi_G = \arctan\frac{L_E}{L_N} = \arctan\frac{V_E * \Delta t}{V_N * \Delta t} = \arctan\frac{V_E}{V_N} \tag{1}$$

Where P_{k-1}, P_k are two consecutive positions from GPS output, ψ_G is the course angle from GPS output, $[L_E\, L_N\, L_U]$ and $[V_E\, V_N\, V_U]$ are the displacement vector and velocity vector of the vehicle in the ENU coordinate system. However, the course angle is only available when the vehicle has a sufficient speed (more than 3 m/s, which is defined empirically). When the speed is lower than the threshold, the performance of the proposed method may be somewhat disappointing [3].

Algorithm framework

Due to the motion characteristics of the vehicle, there is a high degree of consistency between the GPS heading angle and vehicle's true heading angle. In the long run, the GPS heading angle reflects the true heading angle of the vehicle. Based on this characteristic, we propose a GPS/INS integrated navigation kalman filter as shown in Fig. 2.

Where $X_{INERTIAL}$ the state is vector of the inertial navigation system; X_{GPS} is the state vector of GPS; $\Delta\hat{X}_{INERTIAL}$ is the error estimate of the inertial navigation system; ΔX_{GPS} is the measurement noise of the GPS.

DESIGN OF GPS/INS FLITER

State Equation

By defining the ENU coordinate system as the navigation coordinate system, the state equation of the navigation system is:

$$\dot{x}(t) = F(t)X(t) + G(t)W(t) \tag{2}$$

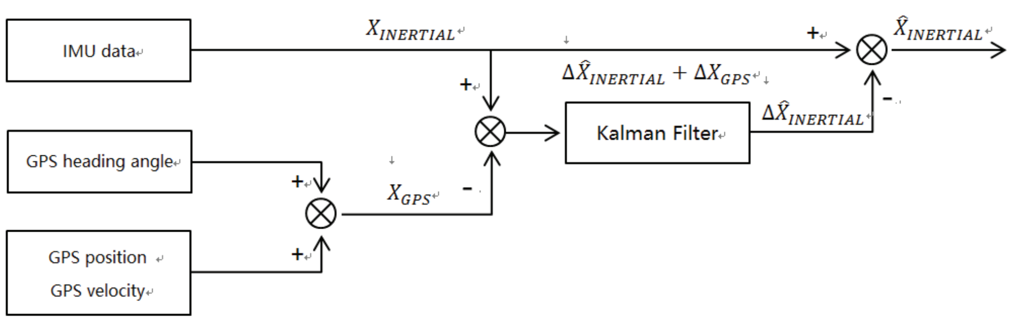

FIG.2 GPS/INS integrated navigation fliter

Where $X = [\delta L\ \delta\lambda\ \delta h\ \delta V_e\ \delta V_n\ \delta V_u\ \phi_e\ \phi_n\ \phi_u\ \varepsilon_{bx}\ \varepsilon_{by}\ \varepsilon_{bz}]$, e,n,u are three axes of the navigation coordinate system; ϕ_e,ϕ_n,ϕ_u are the attitude errors of the platform; $\delta V_e,\delta V_n,\delta V_u$ are the velocity errors; $\delta L,\delta\lambda,\delta h$ are the position errors; x,y,z are three axes of the carrier coordinate system; $\varepsilon_{bx},\varepsilon_{by},\varepsilon_{bz}$ are gyro drifts in the carrier coordinate system.

Discrete the Differential Equation 2:

$$X_k = \phi_{k|k-1} X_{k-1} + \Gamma_{k-1} W_{k-1} \tag{3}$$

Where, W_{k-1} represents the process noise, $\Gamma_{k\text{-}1}$ is the noise driving matrix, and $\phi_{k|k-1}$ is a discrete state transition matrix, which can be expressed by the Taylor series at F_{k-1} with $F_I(t)$:

$$\phi_{k|k-1} \approx I + TF_{k-1} + \frac{T^2}{2!} F_{k-1}{}^2 + \ldots + \frac{T^n}{n!} F_{k-1}{}^n \tag{4}$$

Where I is a unit matrix, and $T = t_k - t_{k-1}$.

Measurement Equation

The position of the inertial navigation system and GPS are:

$$INS: \begin{cases} L_I = L + \delta L_I \\ \lambda_I = \lambda + \delta\lambda_I \\ h_I = h + \delta h_I \end{cases} \tag{5}$$

$$GPS: \begin{cases} L_G = L + \delta L_G \\ \lambda_G = \lambda + \delta\lambda_G \\ h_G = h + \delta h_G \end{cases} \tag{6}$$

Where L_I, λ_I, h_I and L_G, λ_G, h_G represent the latitudes, longitude, height that output by the INS and GPS; $\delta L_G, \delta\lambda_G, \delta h_G$ and $\delta L_I, \delta\lambda_I, \delta h_I$ are latitude, longitude and height measurement noise of GPS and INS; L, λ, h represent the true latitude, longitude, and height of the carrier.

The speed of the inertial navigation system and GPS are:

$$INS: \begin{cases} V_{nI} = V_n + \delta V_n \\ V_{eI} = V_e + \delta V_e \\ V_{uI} = V_u + \delta V_u \end{cases} \tag{7}$$

$$GPS: \begin{cases} V_{nG} = V_n + M_n \\ V_{nG} = V_e + M_e \\ V_{nG} = V_u + M_u \end{cases} \tag{8}$$

Where V_{nI}, V_{eI}, V_{uI} and V_{nG}, V_{eG}, V_{uG} represent the speed output from INS and GPS, M_n, M_e, M_u represent the measurement noise of the GPS, V_n, V_e, V_u represent the true speed of the vehicle.

In order to accelerate the convergence rate of heading angle, the normal method is adding an observation value of GPS heading information [4]. The heading angle of the inertial navigation system and GPS are:

$$INS: \psi_I = \psi + \phi_u \tag{9}$$

$$GPS: \psi_G = \psi + \phi_G \tag{10}$$

Where ψ_I the heading angle of INS is, ϕ_u is the heading error of INS, ψ_G is the heading angle of GPS, ϕ_G is the heading angle measurement noise of GPS, and ψ is the true heading angle.

Considering that the GPS heading error model is complex, we have made a proper simplification of it. The simplified model is as follows:

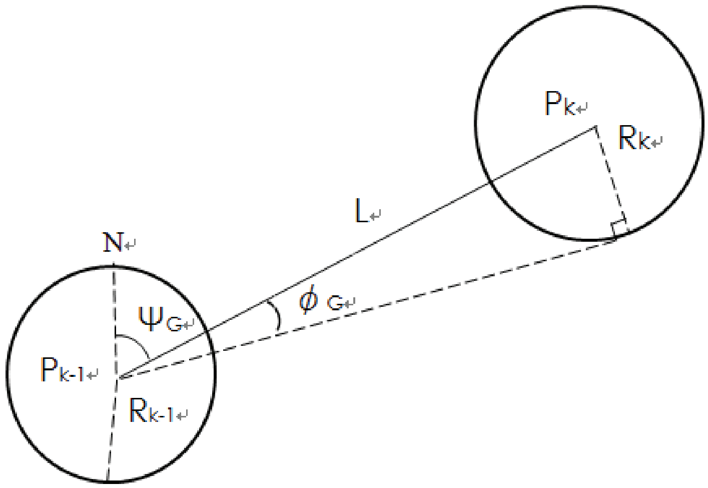

FIG.3 The simplified GPS heading error model

Where P_{k-1}, P_k are two consecutive positions from GPS output; L is the distance between P_{k-1} and P_k; R_{k-1} and R_k are the position errors of P_{k-1} and P_k; N is the north direction of ENU coordinate system, ψ_G is the heading angle of GPS, the heading error is ϕ_G:

$$L{=}V_k * \Delta t \tag{11}$$

$$R_k{=}\delta_p{*}HDOP \tag{12}$$

$$\phi_G = \arcsin\frac{R_k}{L} = \arcsin\frac{\delta_p * HDOP}{V_k * \Delta t} \tag{13}$$

Where V_k is the velocity vector in the navigation coordinate system,and Δt is the measurement interval of GPS. Since Δt is very short, this process can be regarded as uniform rectilinear motion. Assuming that the position measurement error of GPS is Gaussian noise and the variance is δ_p ,The positioning error R_k at P_k can be expressed as $\delta_p * HDOP$, and $HDOP$ is the horizontal accuracy factor of GPS at t_k which can directly parse from the NMEA0183 protocol. Thus, from t_{k-1} to t_k , the measurement error of GPS heading can be regard as Gaussian noise.

Define the measurement vector as follows:

$$Z(t)=\begin{bmatrix} L_I-L_{GPS} \\ \lambda_I-\lambda_{GPS} \\ h_I-h_{GPS} \\ V_{nI}-V_{nG} \\ V_{eI}-V_{eG} \\ V_{uI}-V_{uG} \\ \psi_I-\psi_G \end{bmatrix}=\begin{bmatrix} \delta L_I+\delta L_G \\ \delta\lambda_I+\delta\lambda_G \\ \delta h_I+\delta h_G \\ \delta V_n+M_n \\ \delta V_e+M_e \\ \delta V_u+M_u \\ \phi_u+\phi_G \end{bmatrix}$$

$$=\begin{bmatrix} \delta L_I \\ \delta\lambda_I \\ \delta h_I \\ \delta V_n \\ \delta V_e \\ \delta V_u \\ \phi_u \end{bmatrix}+\begin{bmatrix} \delta L_G \\ \delta\lambda_G \\ \delta h_G \\ M_n \\ M_e \\ M_u \\ \phi_G \end{bmatrix} \tag{14}$$

$$=H(t)X(t)+V(t)$$

The measurement matrix H is:

$$H_{7\times12}=\begin{bmatrix} H_{GPS} & H_\psi \end{bmatrix}^T$$

$$H_{GPS}=\begin{bmatrix} I_{6\times6} & 0_{6\times6} \end{bmatrix}$$

$$H_\psi=\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix}$$

The measurement noise vector is:

$$V=\begin{bmatrix} \delta L_G & \delta\lambda_G & \delta h_G & M_n & M_e & M_u & \phi_\psi \end{bmatrix}$$

Corresponding to the measurement noise vector, the variance matrix is:

$$R(t)=diag\begin{bmatrix} \sigma_{pn}{}^2 & \sigma_{pe}{}^2 & \sigma_{pu}{}^2 & \sigma_{vn}{}^2 & \sigma_{ve}{}^2 & \sigma_{vu}{}^2 & (\arcsin\frac{\delta_p*HDOP}{V_k*\Delta t})^2 \end{bmatrix}$$

EXPERIMENTS AND CONCLUSION

The data is collected in a GPS/INS integrated navigation experiment in Shanghai, and the total time of experiment was about 15 min. The output frequency of GPS and GPS/INS integrated navigation system is 5HZ. The GPS module is known to output 0 deg when the speed is below the threshold. The integrated navigation system starts to initialize when the speed is greater than 3m/s.

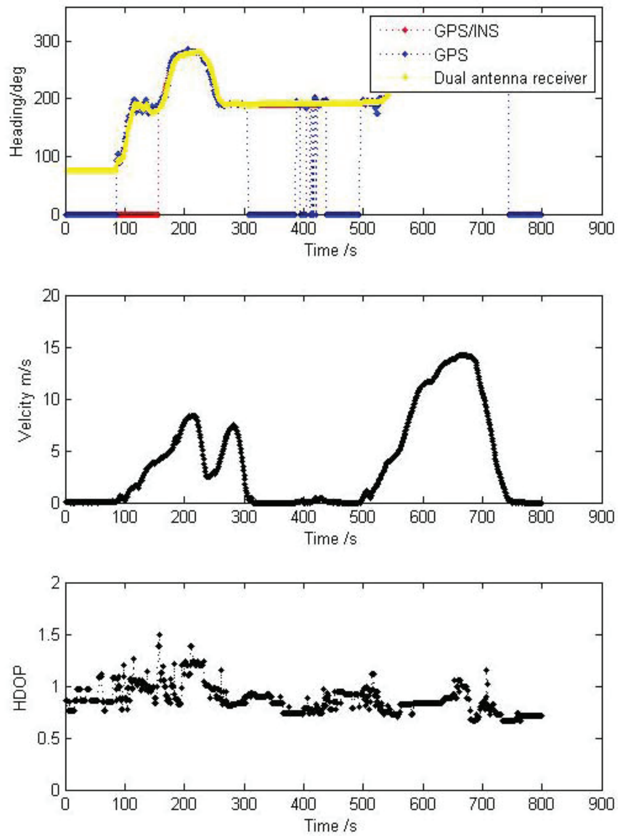

FIG.4 Experiment results

Fig.4 shows the relationship between speed, $HDOP$ and heading angle. Blue line is heading angle of GPS module, red line is heading angle of GPS/INS integrated navigation system, yellow line is heading angle of dual antenna receiver. We will use the output of the dual antenna receiver as a reference.

Define $HDOP \in [0.5, 1]$ as LP and $HDOP \in [0.5, 1.5]$ as HP ,the mean square error of the heading angle in different velocity and $HDOP$ are shown in TABLE Ⅰ and TABLE Ⅱ:

TABLE.1 The Mean Square Error of Heading Angle In Gps

HDOP	Velocity(m/s)				
	[0 ,1)	[1 ,2)	[2, 4)	[4 ,8)	[8 ,16)
HP	6.08	4.54	3.26	2.18	1.01
LP	5.74	4.28	3.16	2.04	0.99

TABLE.2 The Mean Square Error of Heading Angle In Intergrated Navigation System

HDOP	Velocity(m/s)				
	[0 ,1)	[1 ,2)	[2, 4)	[4 ,8)	[8 ,16)
HP	2.52	2.16	1.48	0.96	0.54
LP	2.38	2.07	1.28	0.85	0.52

Ignoring the part where the GPS heading angle equals 0 deg, the increase in speed and the decrease in $HDOP$ will increase the accuracy of the heading angle. Overall, the mean square error of the GPS heading angle is 5.37 deg.

After the GPS/INS integrated navigation system is initialized, the heading error of the integrated navigation system is much smaller than the GPS output, and the mean square error of the heading angle is 2.09 deg.When the velocity is faster than 4m/s, the mean square error is 1 deg or less.

This paper proposes a system that can estimate accurate GPS heading information. Low cost sensors such as GPS are fused with INS through EKF to achieve the desired results [5]. It was shown that the heading angle individually from GPS output equals 0 deg when the velocity is less than the threshold. However, the integrated navigation system does not have this limitation. When the initialization is completed, the integrated navigation system can output continuous, smooth and accurate heading angle and the mean square error of the angle is much smaller than the GPS. It can be eventually concluded that this algorithm can effectively improve the accuracy of GPS heading angle.

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