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4S-Van: A Prototype Mobile Mapping System for GIS

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Abstract : The design of Graphic Information System(GIS) in various applications is suffering from the difficulty of data acquisition, which is labor-intensive and time consuming. In order to provide the spatial data rapidly and accurately, 4S-Van, a prototype mobile mapping system, has been developed. The 4S-Van consists of 1)Global Positioning System(GPS), Inertial Navigation System(INS) for estimating the geographic position and attitude of the moving van, i.e.,(x, y, z) and the direction of the Van, 2) Charge Coupled Device(CCD) camera and laser scanner for capturing images and for measuring depth from geographic objects, and 3) External Synchronization Device(ESD) and industrial PC for synchronizing data from GPS/INS/CCD camera and for storing the data. In this paper, we present the design and implementation of the proto-type 4S-Van system for spatial data acquisition for various GIS applications.

Key Words : GIS, GPS/INS, CCD.

1. Introduction

The 4S-Van is a prototype system for spatial data acquisition. It enables acquisition of the position information and accurate image data of the object by post processing. 4S-Van consists of hardware integration part and post-processing part. The hardware components are GPS, INS, CCD camera, IR camera, ESD, IPC, and laser scanner. The Software components are geo-referencing, 3-D positioning. Fig. 1 shows the architecture of 4S-Van system.

The GPS combined with INS generates data to produce accurate position and orientation information by CDGPS(Carrier Differential GPS) and loosely coupled methods. The CCD camera acquires stereo images of objects. Three-dimensional(3-D) coordinates of various objects included in the stereo images are calculated by using GPS/INS data and internal and external

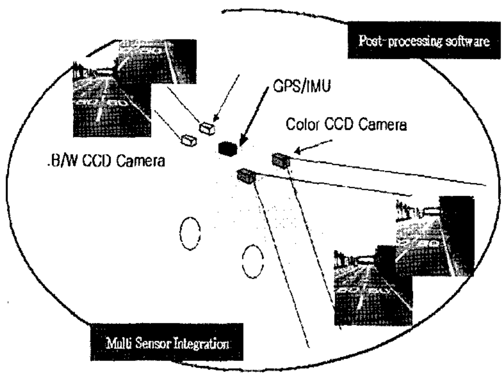

Fig. 1. Architecture of 4S-Van system.

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parameters of CCD camera. The IPC stores images from CCD camera and the ESD generates a pulse to synchronize GPS, INS, image data. The orientation information of the moving 4S-Van is obtained through a geo-referencing process. It consists of GPS/INS integration, self-calibration, and production of exterior orientation of CCD. Finally, 3-D positioning of the object is used to update or create GIS databases. In this paper, we discuss the design of 4S-Van by exploiting a loosely-coupled GPS/INS method, a self-calibration method, and a method to calculate exterior orientation of CCD camera.

The remainder of this paper is organized as follows. Chapter 2 provides calibration and orientation methods for CCD camera. Chapter 3 describes a method for integration of GPS/INS. In Chapter 4, we show the result of performance of 4S-Van's each part. This paper concludes with a summary and our suggestions.

2. Calibration and Estimating Orientation of CCD Camera

To get position of an object using CCD image, lens distortion correction, position and attitude data of camera are essential. In this chapter, we find the lens distortion, exterior orientation parameter(position and attitude of camera), focal length, and principal point by a self-calibration method(Paual and Bon, 2000).

1) Self-Calibration

A self-calibration is a process that adds lens distortion parameter of CCD camera in fundamental space intersection algorithm. That is, self-calibration calculatess exterior orientation as well as focal length, principal point, lens distortion parameter. This method has advantage that it can get exterior orientation as well as focal length, principal point, and lens distortion. The equations are

$$r=\sqrt{(x-x_p)^2+(y-y_p)^2} \quad (1)$$

$$x'=x-x_p+dx_r \quad (2)$$

$$y'=y-y_p+dy_r \quad (3)$$

$$dx_r=(x-x_p)\frac{\Delta r}{r}=(x-x_p)k_1r^2 \quad (4)$$

$$dy_r=(y-y_p)\frac{\Delta r}{r}=(y-y_p)k_1r^2 \quad (5)$$

where $(x_p, y_p)$are principal point, f is focal length, k_1 is distortion parameter, x, y are measured image point, respectively. To get corrected image coordinate, the same numerical formula is used in self-calibration. The following equations are method to get 3-D coordinate of image using acquired exterior orientation.

$$F=(x-x_p)+(x-x_p)(k_1r^2)+f\frac{R}{Q}=0 \quad (6)$$

$$Q=(y-y_p)+(y-y_p)(k_1r^2)+f\frac{S}{Q}=0 \quad (7)$$

$$Q=\mathrm{m}_{31}(X_A-X_L)+\mathrm{m}_{32}(Y_A-Y_L)+\mathrm{m}_{33}(Z_A-Z_L) \quad (8)$$

$$Q=\mathrm{m}_{11}(X_A-X_L)+\mathrm{m}_{12}(Y_A-Y_L)+\mathrm{m}_{13}(Z_A-Z_L) \quad (9)$$

$$Q=\mathrm{m}_{21}(X_A-X_L)+\mathrm{m}_{22}(Y_A-Y_L)+\mathrm{m}_{23}(Z_A-Z_L), \quad (10)$$

where (X_A, Y_A, Z_A) are coordinates of camera position, and $\mathrm{m}_{11} \sim \mathrm{m}_{33}$ are elements rotation matrix.

2) Estimating Camera Orientation

To get the 3-D position of an object, we must calculate orientation of CCD camera. The orientation can be estimated through a process that calculates position and attitude of each CCD by combining position and attitude of CCD with GPS/INS data. Fig. 2 shows flow diagram of exterior orientation data processing in our suggested system.

That is, we get exterior orientation of CCD camera in moving environment by combining GPS/INS data with object coordinates of camera position and attitude. The following equations are used to calculate position of CCD focus.

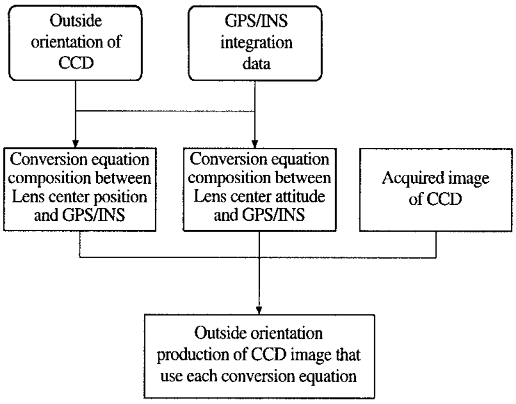

Fig. 2. Architecture of 4S-Van.

$$\begin{bmatrix} X_{ci} \\ Y_{ci} \\ Z_{ci} \end{bmatrix} = M_i^T \begin{bmatrix} X_c - X_G \\ Y_c - Y_G \\ Z_c - Z_G \end{bmatrix} + \begin{bmatrix} X_{Gi} \\ Y_{Gi} \\ Z_{Gi} \end{bmatrix} \quad (11)$$

$$M_i = M_{ki(imu)} M_{\phi i(imu)} M_{wi(imu)} \quad (12)$$

where (X_c, Y_c, Z_c) is the camera center, (X_G, Y_G, Z_G) is the position of GPS when camera acquires an image, (X_{ci}, Y_{ci}, Z_{ci}) is the camera center at time i, (X_{Gi}, Y_{Gi}, Z_{Gi}) is the position at time i, respectively. The following equations are used to calculate attitude of CCD focus.

$$\omega_{ci} = \omega_{Ii} + \Delta\omega \quad (13)$$

$$\phi_{ci} = \phi_{Ii} + \Delta\phi \quad (14)$$

$$k_{ci} = k_{Ii} + \Delta k \quad (15)$$

$$\Delta\omega = \omega_c - \omega_I \quad (16)$$

$$\Delta\phi = \phi_c - \phi_I \quad (17)$$

$$\Delta k = k_c - k_I, \quad (18)$$

where (ω_c, ϕ_c, k_c) is attitude parameters for CCD camera, (ω_I, ϕ_I, k_I) is the attitude of INS when camera acquires an image, $(\omega_{ci}, \phi_{ci}, k_{ci})$ is the camera attitude at time i, $(\omega_{Ii}, \phi_{Ii}, k_{Ii})$ is the INS attitude at time i, respectively.

3. GPS/INS Integration

While GPS provides position and velocity data with long-term stability, INS provides high-rate position and velocity data with short-term stability. By integrating the GPS with INS, an enhanced navigation system can be achieved to provide highly accurate navigation data. For the GPS/INS integration, there are required error model of INS and navigation equation(Kaplan, 1996; Greenspan, 1996).

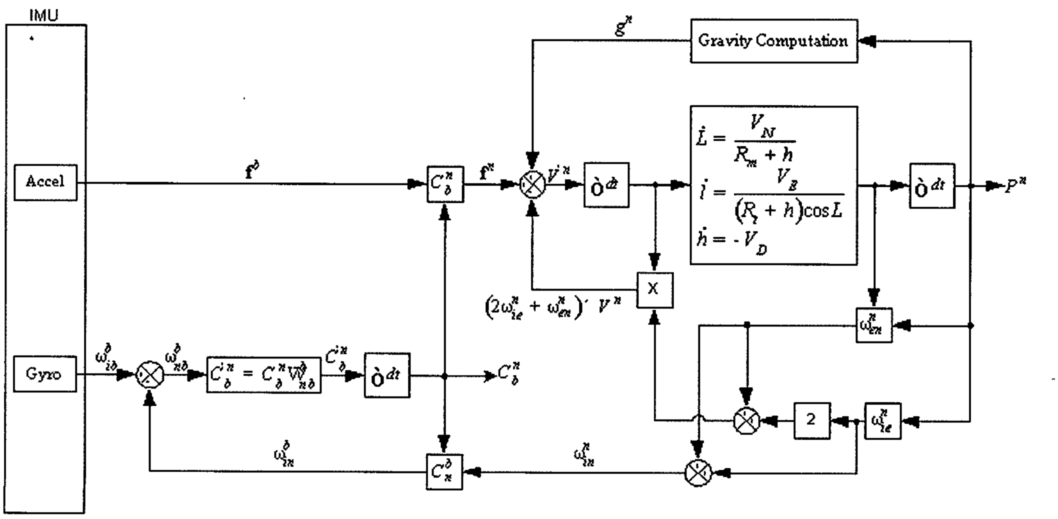

Fig. 3. Architecture of strap-down INS.

1) INS Navigation Equation

Strapdown INS Navigation algorithms consists of attitude, position, and velocity equation. Attitude algorithms are divided into quaternion update method, direction cosine matrix, and euler angle. In this paper, quaternion is used for obtaining an accurate and fast attitude of the vehicle. The velocity and position algorithm can be written as

$$\dot{v}^n = C_b^n f^b - (2w_{ie}^n + w_{ie}^n) \times v^n + g^n \tag{19}$$

where C_b^n, g, f, and w are transformation matrix between body frame and navigation frame, normal gravity vector, specific force vector, and angular velocity vector, respectively.

2) INS Error Model

The application of the Kalman filtering technique combining INS and the GPS requires mathematical error model of INS and GPS system. Several forms of INS error models have been developed till present. It is proved that all these error models are actually equivalent and can be derived in a unified approach. In this paper, the following φ error model is applied.

$$\frac{d}{dt}\delta v^n = -\delta(w_{in}^n + w_{ie}^n)v^n - (w_{in}^n + w_{ie}^n)\delta v^n + \delta a^n + \frac{\partial_g^n}{\partial_p^n}\delta p^n + \delta a^n \tag{20}$$

$$\delta_\varphi^n = -w_{in}^n \times \varphi^n - C_b^n \delta w_{ib}^b + \delta w_{in}^n \tag{21}$$

where a^n, p^n, v^n, φ^n are the acceleration error, position error, velocity error, and attitude error, respectively.

3) GPS/INS Integration Filter Design

The GPS/INS Integration system is usually configured in a tightly-coupled method or a loosely-coupled method. Specially, the loosely-coupled method has an advantage of simple structure and easy implementation.

There are two error calibration techniques for implementation of GPS/INS integration system: the feedforward method and feedback method. In this paper, loosely-coupled method is applied for the integration design, and feedback update technique is applied for the calibration of system errors(Brown and Hwang, 1997; Titterton and Weston, 1997). The state equation of Integration Kalman filter are as

$$\dot{X} = FX + GW \tag{22}$$

$$F = \begin{bmatrix} F_{11} & F_{12} \\ 0_{9\times 9} & 0_{9\times 9} \end{bmatrix} \tag{23}$$

$$G = \begin{bmatrix} C_b^n & 0_{3\times 3} \\ 0_{3\times 3} & D^{-1}C_b^n \\ 0_{3\times 3} & 0_{3\times 3} \end{bmatrix} \tag{24}$$

where X is navigation error state, G is noise input matrix, W is zero-mean gaussian white noise; and the sub-matrices F_{11} and F_{12} are given by

$$F_{12} = \begin{bmatrix} C_s^n & 0_{3\times 3} & 0_{3\times 3} \\ 0_{3\times 3} & D^{-1}C_s^n & D^{-1}C_s^n diag(a^s) \\ 0_{3\times 3} & 0_{3\times 3} & 0_{3\times 3} \end{bmatrix} \tag{26}$$

$$F_{11} = \left[\begin{array}{cccccccccc} & 0 & -W_e\sin(\phi) & 0 & 0 & \cos(\phi) & 0 & -W_e\sin(\phi) & 0 & 0 \\ & W_e\sin(\phi) & 0 & W_e\cos(\phi) & -1 & 0 & 0 & 0 & 0 & 0 \\ & 0 & -W_e\cos(\phi) & 0 & 0 & -\sin(\phi) & 0 & -W_e\cos(\phi) & 0 & 0 \\ -a & 0 & \frac{-a^3}{r} & \frac{a_2}{r} & 0 & -W_e\sin(2\phi) & 0 & 0 & 0 & 0 \\ & \frac{a^3}{r\cos(\phi)} & 0 & \frac{-a_1}{r\cos(\phi)} & 2W_e\tan(\phi) & 0 & \frac{-2W_e}{r} & 0 & 0 & 0 \\ & a_2 & -a_1 & 0 & 0 & 2rW_e\cos^2\phi & 0 & 0 & 0 & 0 \\ & 0_{3\times 3} & & & I_{3\times 3} & & & & 0_{3\times 3} & \end{array}\right] \tag{25}$$

The measurement equation is written as

$$Z = Hx + V \tag{27}$$

where Z is input measurement of kalman filter, V is measurement noise, H is measurement matrix

$$H = (0_{6\times3} \quad I_{6\times6} \quad 0_{6\times9}) \tag{28}$$

4. Test Results

1) Self-Calibration

After establishing calibration target for Self-calibration test, we measured accurate position of each target by GPS and total station.

The target itself has a 52 grid blocks over a wall, with the dots located in the middle of grid blocks. To collect the calibration data, the images of the target board were taken at three different positions where all dots in the targets are clearly visible in each image. Fig. 4 shows calibration target for self-calibration test.

Also, after measuring each target by 4S-Van, we

Table 1. Exterior orientation of CCD camera.

	Camera 1	Camera 2
X(m)	-0.173586	-0.089520
Y(m)	0.601111	0.641841
Z(m)	3.789430	3.743983
Omega(rad)	-0.091472	-0.083936
Phi(rad)	-0.011572	-0.006811
Kappa(rad)	0.026546	0.029131

Table 2. CCD Camera parameters.

	Camera 1	Camera 2
Focus length(mm)	10.262043	9.698757
Principal point x (mm)	-0.265375	-0.168290
Principal point y(mm)	0.851428	0.988679
Radial distiortion	0.032464	0.030344

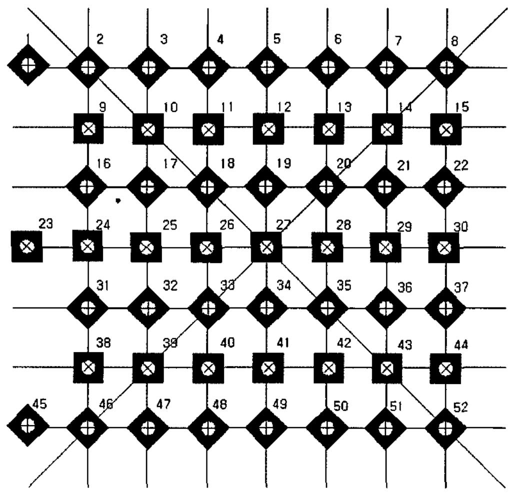

Fig. 4. Calibration target.

Table 3. Position of space intersection method.

ID	X direction(m)	Y direction(m)	Z direction(m)
1	0.004053	0.004312	0.031481
2	5.42E-05	0.003528	0.004697
3	0.001119	0.00351	0.023237
4	0.001813	0.004768	0.013425
5	0.005952	0.006996	0.037186
6	0.004135	0.001589	0.005886
7	0.001084	0.000977	0.002902
8	0.000385	0.000376	0.008664
9	0.000524	0.001428	0.014051
10	0.00048	0.001388	0.003367
11	0.004258	0.002381	0.014304
12	0.008252	0.000754	0.014575
13	0.003917	0.002351	0.000894
14	0.000479	0.006771	0.019897
15	0.000139	0.004408	0.008875
16	0.000777	0.005016	0.011781
17	0.006791	0.001328	0.018483
18	0.011233	0.004792	0.029572
19	0.004481	0.006791	0.015324
20	0.001793	0.010541	0.028265
21	0.00098	0.012508	0.03561
22	0.00075	0.009179	0.021573
23	0.00156	0.009673	0.030194
24	0.001088	0.013069	0.032637
25	0.003018	0.005431	0.008492
26	0.012624	0.006161	0.026908
(RMSE)		**0.019223**	

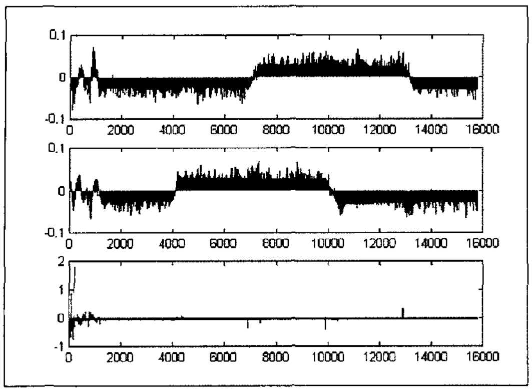

Fig. 5. Attitude error of simulation.

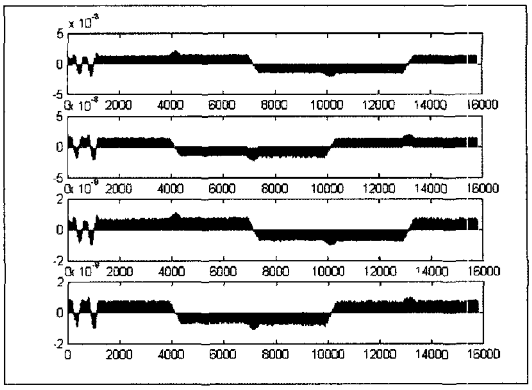

Fig. 6. Velocity and position error of simulation.

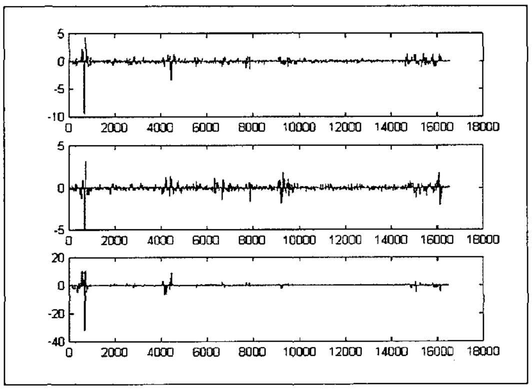

Fig. 7. Attitude error of vehicle test.

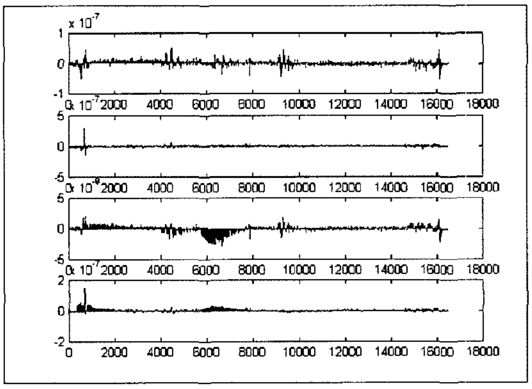

Fig. 8. Velocity and position error of vehicle test.

processed measured data by self-calibration method. Finally, we compared acquired position by self-calibration with acquired position by total station, and verified performance of self-calibration method. The following tables are the results of self-calibration, where camera1 is left CCD camera and camera2 is right CCD camera of vehicle. Table 1 shows exterior orientation of CCD camera and Table 2 shows information about lens distortion

Furthermore we calculate 3D position of target by space intersection method to verify result of camera calibration/bundle adjustment. Table 3 shows the position difference of acquired position by self-calibration and acquired position by total station.

2) GPS/INS Integration

This paper uses a crossbow's INS, VG600CA, low cost INS with three fog gyros and three accelerometers. INS has gyro biases of around 0.03 degree per second and accelerometer biases of around 8.5mg. In order to test performance of GPS/INS Integration algorithm, we experimented by two methods. One is matlab simulation and the other is vehicle test. Matlab simulation was done to evaluate the designed integration algorithm performance in computer. Also, we attached GPS/INS on roof of vehicle for vehicle test. Fig. 5 and Fig. 6 show simulation results, and Fig. 7 and Fig. 8 show vehicle test results.

In the test results, simulation data error is smaller than vehicle test error. But both results don't meet final performance requirement of 4S-Van.

5. Conclusions

In this paper, we suggest the design of 4S-Van using GPS/INS loosely-coupled integration and self-calibration algorithm. GPS/INS loosely-coupled integration provides position and attitude data of moving vehicle, and self-calibration algorithm provides position, attitude, and lens error correction data of CCD camera. The performance of the 4S-Van's each part is evaluated through the computer simulation and the vehicle tests. Test results show that the performance of the integrated GPS/INS should be implemented. As a further study, tightly-coupled method should be considered to achieve better accuracy under dynamic environments. Furthermore, the following aspects have to be investigated more: 1)time synchronization between GPS/INS and CCD camera, 2) error correction between GPS/INS and CCD camera, 3) minimizing vibration effects of vehicles, and 4)error correction method due to multi-sensor integrations.

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