Design of a Mobile Mapping System for GIS Data Collection

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Data acquisition is the most expensive part of establishing a Geographic Information System (GIS). A mobile mapping system, the GPSVision, which integrates the Global Positioning System (GPS), an Inertial Navigation System (INS) and stereo cameras, has been developed to quickly and accurately collect the digital data of civil infrastructures. While the mobile mapping system drives at a normal speed, the GPS and INS record the position and attitude information of the system, and the stereo vision system takes image pairs at regular interval. After GPS/INS data is processed, the position and orientation of every image pair is determined in the global coordinate system. Any features which are visible on an image pair can be located in a global coordinate system.

The GPS provides accurate position data. Because of low data rates and a requirement of viewing at least four satellites, the use of GPS alone is limited. In contrast, the INS provides high rate position and attitude information, but its sensor errors tends to grow with the time. By integrating GPS and INS, the accurate GPS position is used to update the INS, and the INS then produces high rate, accurate position and attitude data, even when the GPS signals are lost.

From an application perspective, a mobile mapping system can be used to collect stereo digital images along highways, state roads and residential streets, while traveling at posted speed limits. These digital images are accessed by feature extraction software to locate the positions of visible physical facilities, such as manholes, curb lines, traffic signs, pedestals and building locations. The positions and attributes of these visible features are stored in a simple format which is transportable to standard GIS systems. Once the processed data is loaded into the target GIS, the data is displayed in map format and manipulated utilizing database query functions. A typical client could use these data to accurately position traffic signs, develop base maps or view image data as one drives down the road.

This paper will discuss the basic issues of a mobile mapping system. A brief description of the system configuration is given, followed by the integration of GPS/INS using a kalman filter, and system calibration for determining the offsets between the different sensors. How the position and attributes of a feature is collected and transferred into a GIS are addressed. Automatic information extraction from image pair is also discussed. Finally, the data sets collected by a mobile mapping system are presented to demonstrate the efficiency and applications of the mobile mapping system.

1. Introduction

Generation of the civil infrastructure is an immense task. It requires efficiently collecting vast quantities of data. New technologies offer opportunities to greatly improve our effectiveness. One of the most innovative technologies for collecting civil infrastructure data is the GPSVision -- a Mobile Mapping System developed by Lambda Tech International, Inc. The GPSVision quickly acquires highly detailed, multimedia data about highways, railroads and other transportation networks. It uses the Navstar Global Positioning System(GPS), integrated with an Inertial Navigation System(INS) along with a state of art color CCD cameras. The result is that any feature (e.g. a manhole) which is "seen" by two cameras can be precisely located in a global coordinate system.

A GPS receiver determines the global location of the system. Depending on the type of the receiver and the processing software used, positioning accuracy can range from meters to centimeter. Because obstructions such bridges, trees, tunnels or high rise buildings can interrupt satellite signals, GPS alone can not meet the requirement for a mobile mapping system. An INS consists of the accelerometer and gyroscopes. It is a self contained system. It measures the velocity and direction changes very accurately for short periods, but its error grows rapidly with time. An integration solution of GPS and INS can greatly improve the system performance. GPS is used to update the INS system and the INS outputs the accurate position, velocity and attitude of the system between the GPS updates.

The stereo vision system consists of two high resolution color CCD cameras. It captures stereo image pairs while the system drives at posted speeds. The images are taken according to a distance interval to provide a full coverage of the road way and its surroundings. By applying photogrammetric triangulation technology, any point that appears in both images can be located into a global coordinate system.

In order to perform precise positioning, it is necessary to calibration the entire system. The camera geometry, the lens distortions, the relative orientation parameters and the offset between the stereo vision system and GPS/INS system must be determined. The camera geometry may be constant for long time, but the relative and rotation offsets may change between the different missions. The entire system calibration are divided into two parts. The first part is the calculation of camera parameters using known control points in a test-field, the second is the calculation of the relative orientation and rotation offset based on the coplanarity equation and constraints. In the second part, the position and rotation parameters of an image pair is used. No additional controls are required. This is well-suited for the mobile mapping system.

Data from the GPSVision are converted into a format directly acceptable for entry into a GIS. After the information is analyzed, highway officials or utility companies use it to support management decision making. The GPSVision is an ideal platform for cost-efficient multimedia collection of the spatially-referenced digital data that is highly accurate, current, homogeneous and consistent, and therefore, well-suited for the generation of a land-based geographic information system.

2. System Configuration

The hardware component of the first generation of the GPSVision consists of three major components: a Trimble ProXL code-phase GPS receiver, a Liton LN-200 inertial navigation system and two color CCD cameras. The GPSVision is a very flexible system, many different types of GPS receivers or cameras are also used in the GPSVision system depending on the application requirement, e.g. The Trimble SSI GPS receiver is used to achieve the point accuracy for 10 to 20 cm. The other important feature is its independence with the moving platform, it is portable and can be mounted on different vehicles. Fig. 1 shows the GPS receiver, the left camera and the INS system which are inside the box.

Fig. 1 The GPS, INS and left camera of the portable GPSVision system

A PC-computer provides for the overall control, storage, display and operator interaction during the data acquisition. It is constructed on a passive backplane chassis and mounted in a rugged industrial chassis with a single board CPU. The single board CPU is a 486 DX/66MHz PC executing a standard multi-tasking operating system. The backplane also has an INS interface consisting of a SDCC digital interface, Built-In-Test (BIT) board, and a timing interface board. In addition to the boards, the chassis will also contain a solid state or standard storage device and a boot device.

The Built-In-Test Diagnostic System provides hardware status of all sub-systems to the operator and warns of pending maintenance action or failure. The BIT consists of a digital I/0, a digital to analog converter and an analog to digital converter board for monitoring each subsystem

The GPS unit provides the system computer with GPS timing, distance measurements, satellite data and satellite status information. The solid state INS provides changes in direction and speed data. The GPS time is unique and all collected data are correlated on the GPS time. All data are stored in a binary format and used in post-processing software.

The vision system consists of two high resolution color CCD cameras that provide overlapping stereo images, two digital frame buffers and an optical disc recorder. The cameras are progressive scan CCD units with auto IRIS wide angle lenses. The image capture of stereo image pairs is user configurable by distance or time. For example, a stereo pair of images can be captured at an interval of 16 meters.

The operator interface consists of a laptop computer running Microsoft DOS / Windows. The laptop is connected to the PC-computer through a network device. It acts as a terminal for control and a digital storage device.

3. Positioning

The Positioning procedure of the GPSVision consist of two steps: determining the position and rotation of the image pair in a global coordinate system and the positioning of an object from an geo-referenced image pair. The first step is to combine the GPS and INS data using the kalman filter method and determine the 6 necessary parameters (three position parameters and three rotation parameters) of the GPSVision at the time when an image pair is taken. The second step determines the three-dimensional coordinate of an object by a photogrammetric triangulation and transfers it into the global coordinate system.

In the GPSVision system, the GPS receiver, INS and two CCD cameras are mounted on a stationary platform. Their relative position is stable during a survey. Once the camera parameters and the relative orientation parameters are known, a three-dimensional local coordinate of an object can be calculated from its left and right image coordinates. After mathematically correcting the position and rotation offsets, the local coordinate can be transferred into a global coordinate system. In the following, the positioning procedure of the GPSVision is presented.

3.1 Differential GPS Positioning

Depending on the type of GPS receiver, the GPS processing software varies. In the first generation of the GPSVision system, the code-phase submeter receiver is used. The C/A peudoranges are used for differential positioning. We process the GPS data by first forming the distance double difference between two satellite (i), (j), base receiver (b) and the rover GPS receiver (r) by :

$$R_{rb}^{ij} = R_r^i - R_r^j - R_b^i + R_b^j \qquad (1)$$

The double difference of the pseudo range distance equals the double difference of calculated distance using their coordinates:

$$R_{rb}^{ij} = \rho_{rb}^{ij} \qquad (2)$$

The unknowns parameters are the three coordinate of the rover GPS receiver, since the location of satellite and base station are known. We get the observation equation for one double difference observable after linearizing (2):

$$\begin{aligned} v_{rb}^{ij} + R_{rb}^{ij} = \rho_{rb}^{ij} &+ \left(\frac{X^i - X_b}{\rho_b^i} - \frac{X^j - X_b}{\rho_b^j}\right) dX_b \\ &+ \left(\frac{Y^i - Y_b}{\rho_b^i} - \frac{Y^j - Y_b}{\rho_b^j}\right) dY_b \\ &+ \left(\frac{Z^i - Z_b}{\rho_b^i} - \frac{Z^j - Z_b}{\rho_b^j}\right) dZ_b \end{aligned} \qquad (3)$$

At least three double difference observations are needed to solve three unknowns. This requires at least four common satellites in view. As the GPSVision is moving, its position is calculated on an epoch by epoch basis whenever four or more satellites are tracked.

3.2 INS Positioning

The measurement of an inertial system come from two sensor triads, an accelerometers block and a gyro block. They are defined as three components of the specific force vector f and three component of the body rotation rate. The body rotation rates are measured as angular velocities with respect to the inertial frame. All measurements are given in body frame coordinate.

According to the Newton's second law of motion in the gravitational field of the earth (i-frame):

$$\ddot{r}^i = f^i + g^i \qquad (4)$$

where r is the position vector, f is the specific force and g the gravitation in inertial frame (i). After considering the earth rotation, the equation (4) can be written in a local coordinate system (n-frame) defined by Easting, Northing and Upward in the ellipsoid with a set of first order differential equations as :

$$\begin{pmatrix} \dot{r}^n \\ \dot{v}^n \\ \dot{R}_b^n \end{pmatrix} = \begin{pmatrix} v^n \\ R_b^n f^b - (2\Omega_{ie}^n + \Omega_{en}^n) + g^n \\ R_b^n \Omega_{bn}^b \end{pmatrix} \qquad (5)$$

where the n represent the local coordinate system, r is position vector and v is velocity, R_b^n is rotation matrix from body frame (b) to local frame (n), and Ω_{bn}^b is the skew matrix of the body rotation rate with respect to the local frame.

3.3 GPS/INS integration

The integration of GPS/INS can be performed at different levels and using different methods. The kalman filter is considered as a common method. The state vector includes attitude, position, velocity, accelerometer biases and gyrodrifts:

$$X = (\varepsilon, \delta_r, \delta_v, d, b)^T \qquad (6)$$

The linear dynamic model for the kalman filter is formed by linerizing equation (5) and adding the error model of gyrodrifts and accelerometer biases:

$$\dot{X} = FX + W \qquad (7)$$

or for the discrete measurement:

$$X_{k+1} = \Phi_k X_k + W_k \qquad (8)$$

where X is the state vector, W is the system noise and is ϕ is the transition matrix. For a short time interval $(t - t_0)$, F can be considered as a constant and ϕ is defined by :

$$\Phi = I + F(t - t_0) \qquad (9)$$

The kalman filter consists of a prediction and an update. From time k to k+1, the prediction is:

$$\begin{aligned} X_{k+1}^- &= \Phi_k X_k^+ \\ P_{k+1}^- &= \Phi_k^T P_k^+ \Phi_k + Q_k \end{aligned} \qquad (10)$$

were (+) represents the updated value and (-) the predicted value.

The kalman gain matrix is defined by :

$$K_k = P_k^- H_k^T (H_k P_k^- H_k^T + R_k)^{-1} \quad (11)$$

The update procedure is :

$$\begin{aligned} X_k^+ &= X_k^- + K_k(Z_k - H_k X_k^-) \\ P_k^+ &= K(I - K_k H_k) P_k^- \end{aligned} \quad (12)$$

where Z is measurements, H establishes the linear connection between the Z and X.

To use the kalman filter to integrate the data from different sensors are straight forward, but modeling the statistical properties of these parameters are not always possible. Therefore, the design of the filter is a compromise between theory and practice. The decentralized filter method is chosen for our case, because it is simple and flexible. Fig. 2 shows the procedure of this method.

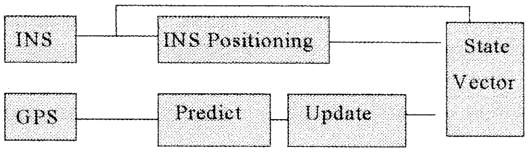

Fig.2 The GPS/INS integration procedure

The Kalman filter is a very sophisticated method. After establishing the dynamic model of the system, the kalman prediction estimates the state vector and its covariance matrix of the system. Whenever a measurement is available, the kalman update will use it to calculate more accurate state vector and covariance. This will repeat until all data is processed. In the GPS/INS integration, the data from the INS is very accurate for a short period, so instead of using the kalman prediction, the INS positioning equation (5) is used as the prediction module. To achieve the most smooth result, the Kalman filter is used in forward and backward. Fig. 3 shows a data set after the GPS/INS integration.

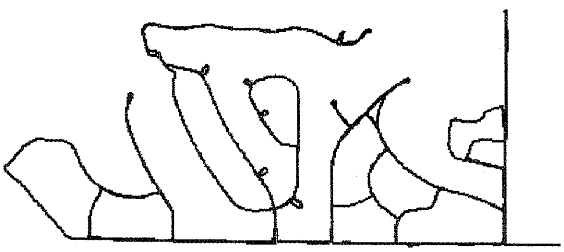

Fig. 3 The GPSVision creates the street map of Bayside in Wisconsin, USA

3.4 Positioning with stereo images

After the GPS/INS integration, every image pair taken by the stereo cameras is georeferenced with three position parameters and three rotation parameters. After calibration procedure, the inerior, relative orientation parameter and the offset parameter between the different sensors are available. A three-dimensional coordinate of an object is calculated by a photogrammetric intersection procedure using its left and right image coordinate. The following formula is used to transfer it to a Earth-Fixed coordinate system.

$$X^e = X_{ins}^e + R_n^e R_b^n R_r^b (R_v^r X^v + D_{rb}^r) \quad (13)$$

where

- X^V 3-D coordinate in the vision frame with the origin at left camera, the X-axis pointing to right camera and the Y-axis parallel to image frame and pointing up.
- R_v^r 90-degree rotation from vision frame to reference frame. It rotate the Z-axis to the vertical direction.
- D_{rb}^r Origin of INS body frame (b) defined in r-frame.
- R_r^b Rotation from the reference-frame (r) to INS body-frame (b). This matrix is determined in the calibration procedure.
- R_b^n Rotation from INS body frame (b) to the local frame (n) defined by Easting, Northing and Upward direction on the ellipsoid. The rotation angles (pitch, roll and azimuth) are obtained from the INS system.
- R_n^e Rotation from local frame (n) to Earth-fixed frame (e).
- X_{ins}^e Coordinate of the INS system in Earth fixed frame when image pair was taken.
- X^e Coordinate in Earth fixed frame.

The geographic coordinate (ϕ, λ, h) is obtained from the Earth-Fixed coordinate X^e by a simple transformation. Other map coordinates, e.g. UTM, State plane, can be also obtained according to the application requirement.

4. Feature Extraction and Applications

The stereo vision system of the GPSVision system is designed to collect features from the real world. After data collection in the field, the GPS and INS data are processed and combined together. Every image pair is tagged with its position and rotation in a global coordinate system and is used for extracting useful information.

The Feature Extraction software is developed on Microsoft Windows NT/95 operating system and is external rule based driven and language neutral. The user will interact with the software and point at features of interest in the stereo image pairs. The software then triangulates the relative position of the selected feature and transfer it into the global coordinate system.

In addition to calculating locations, the software will provide for the selection, control and display of the video images. A map window display the tracking of the GPSVision, the image location and the extracted features. An image pair is selected from the map window or using forward/backward image function. The image can be viewed in the zoom mode and its contrast is easily adjustable. The user selects the active feature and assigns attributes to it. After measuring the left and right image coordinate, the global coordinate or the distance measurement is also displayed.

By using the image matching method, the features are positioned by selecting a point on one of the stereo images. It reduce the feature extraction time by half. Another application of the image matching technology is to measure the profile and surface of object.

The stereo vision system of the GPSVision collects huge amount digital data. Automated feature extraction is very important to the mobile mapping system, but it is still in the research step. One test has been done with automatic extraction of the road edge lines, it works with the well-painted road edges, but it still can't be used in the production. The automated relative orientation and triangulation could be implemented for the mobile mapping system, but they are not so critical, because these procedures do not require to much effort to be performed by a person. How to more efficiently extract the information from stereo images will be the next focus of our new development.

After the feature extraction, a standard output file is created which contains all feature information about the collected features. The Re-Formatting software processes the standardized output files of the Feature Extraction Software and create the required input files for the targeted AM/FM or GIS system. Like the Feature Extraction Software the Re-Formatting Software packages will use the same external rule files to control the processes.

The GPSVision is a data acquisition tool to create the land-based digital information. In the couple months after the GPSVision is in operation, several applications have been accomplished. The street center lines created by the GPSVision are used to rectify aerophotographies for Gas company in Wisconsin. Infrastructure elements, like, manholes, fire hydrants, collected by the GPSVision are used for management and planning by the city of Hopkins, Minnesota. A company in Thailand, Real Time, Ltd., uses the GPSVision to map the city of Bangkok. Experiences show that the data acquisition procedure by the GPSVision is fast, accurate and lower cost than traditional methods.

Fig. 4 Georeferenced stereo image pair taken from Bangkok, Thailand. Two poles and one manhole are extracted from this image pair.

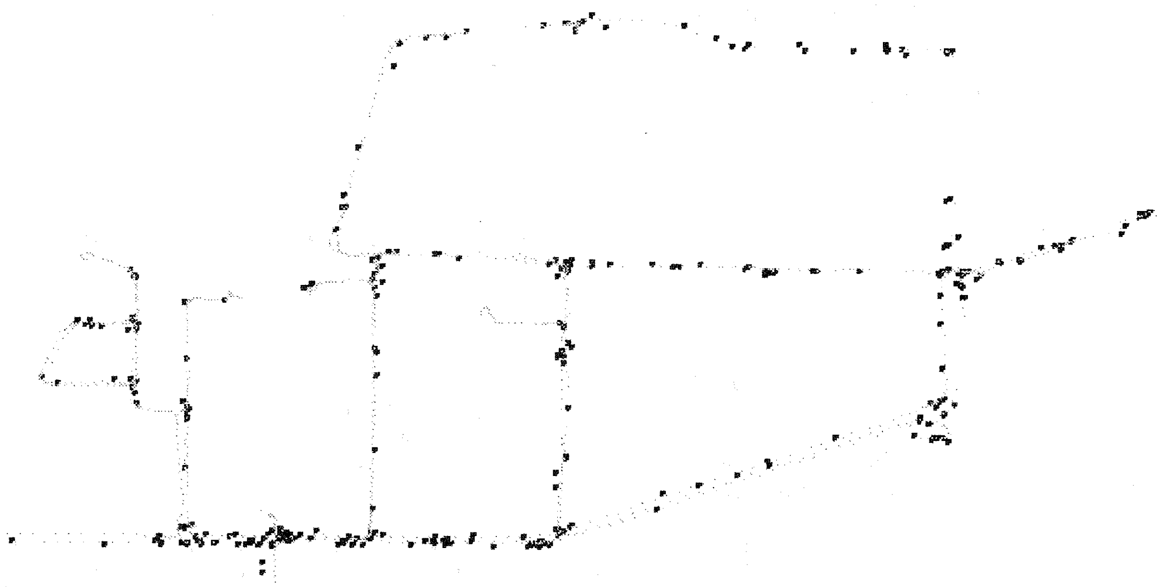

Fig. 5 City infrastructure map of city Hopkins, Minnesota, USA, created with GPSVision system with submeter accuracy.

5. Conclusion

In this paper, the design of a mobile mapping system is presented. Integration the GPS, INS and stereo cameras on a moving platform enable us to efficiently collect huge amounts of digital data for GIS application. Every object which is seen on the stereo images can be positioned in a global coordinate system together with its attributes. All data collected can be transferred into common GIS systems. Data collected using the GPSVision meets the requirements of most engineering applications. Several project have been completed successfully.

Automatic extraction of the features is a very important issue for mobile mapping application, it will greatly improve the data extraction procedure. Integrating other hardware, like a laser range finder, will bring the new abilities of the mobile mapping system. These are two major development in the future.

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