STUDY ON KEY TECHNOLOGIES OF VEHICLE-BORNE MOBILE MAPPING SYSTEM INTEGRATED WITH GPS/INS/CCD CAMERAS

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ABSTRACT

Direct positioning and data acquisition system, composed of global positioning system (GPS), inertial navigation system (INS), laser ranging technique and digital photogrammetry, is a fast data acquiring technique developed in the field of surveying and mapping in recent years. Focusing on data acquisition based on vehicle-borne mobile mapping system integrated with GPS/INS/CCD cameras, this paper studies such key technologies as system calibration and stereo image matching. Through the system calibration, the paper gives direct positioning equation of vehicle-borne stereo photogrammetry system, which can work out 3D geospatial coordinates of pixel directly. Through stereo image matching, conjugate points in stereo image can be automatically found. Furthermore, the paper develops 3D data acquisition system based on vehicle-borne stereo images, and gives experimental results by taking real geospatial coordinates collection of ground objects as examples. The experimental results show that vehicle-borne mobile mapping system can play an important role in acquisition, processing and model construction of city 3D spatial information efficiently, quickly and accurately.

Keywords: vehicle-borne mobile mapping system, spatial data acquisition, stereo photogrammetry, system calibration, stereo image matching

1. INTRODUCTION

With the development of society and economy in recent years, the demand of 3D geospatial data quick acquisition is increasing year by year. Thus the development of new techniques for geospatial data quick acquisition have been attracted more and more attentions by governments and academia. Especially, the problem that how to acquire real geospatial coordinates of ground objects under the condition of no ground control points is a hot spot. Because global positioning system (GPS) and inertial navigation system (INS) have different advantages in position, attitude and velocity measurement respectively, and can overcome shortcomings each other in technology, the combined navigation systems integrated with GPS and INS have been studied and applied more and more by lots of researchers.

In recent years, the technology of mobile mapping system integrated with multi-sensors has grown rapidly. Different types of air-borne and vehicle-borne 3D data acquisition system integrated with GPS, INS, laser scanner, and CCD camera were developed for geospatial data acquisition. In 1999, OEEPE (European Organization for Experimental Photogrammetric Research) started up an experiment named as ‘Integrated Sensor Orientation’, and obtained many theoretical results, which

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played an important guidance role on the application of GPS/INS combined system in the field of photogrammetry and remote sensing[1]. Tokyo university did a lot of research in the vehicle-borne laser scanning system from 2000, and used this system to construct CAD models of buildings and update city GIS database[2,3]. The University of Calgary developed an air-borne digital multi-sensor system with GPS/INS, and tested this system for digital mapping data acquisition[4]. The Ohio State University developed an high-accuracy direct aerial platform orientation with tightly coupled GPS/INS, and used this system to capture 3D data of roads[5]. Besides above air-borne mobile mapping systems, different types of vehicle-borne mapping system integrated with GPS, INS, laser scanner, and CCD cameras are also preliminarily applied in the field of 3D data acquisition. Abuhadrous[6] studied data processing method of vehicle-borne laser scanning system, developed corresponding data post-processing software, and used this system to digitize and construct 3D model of urban environments and roads. Grinstead[7] developed a vehicle-borne scanning system, and utilized this system to construct surface model of buildings and generate 3D terrain model. Cole[8] studied 3D simultaneous localization and mapping algorithm for processing laser range data, and used this algorithm to construct 3D models of outdoor environments. Asai[9] and Ishikawa[10] also did a lot of research on data capture and process for vehicle-borne data acquisition system integrated with multi-sensors. In China, the research of vehicle-borne mobile mapping system is behind western developed countries. However, Wuhan University, Shandong University of Science and Technology, and Nanjing Normal University have acquired many results on development of hardware and software for vehicle-borne mobile mapping system integrated with multi-sensors[11~14].

Considering characteristics of stereo photogrammetry system in vehicle-borne mobile mapping system, this paper focused on solving such key technologies as system calibration and stereo image matching for automatically obtaining geospatial coordinates of ground objects. Based on paper’s data processing methods, the data processing software for vehicle-borne stereo photogrammetry system was developed. Application examples of our mobile mapping system were given in this paper. Experimental results show that paper’s algorithms are simple and comprehensible, and have an important reference role on practical application of vehicle-borne mobile mapping system.

The organization of this paper is given as follows: The research background is introduced in section 1. Brief introduction of our vehicle-borne mobile mapping system is given in section 2. Description of the proposed approach is given in section 3. The experimental results and discussions are summarized in section 4.

2. BRIEF INTRODUCTION OF SYSTEM HARDWARES

Our vehicle-borne mobile mapping system was developed by Nanjing Normal University and Wuhan University, its appearance is shown in Fig.1. In vehicle platform, there are such equipments as a suit of difference GPS/INS system, four CCD cameras, three linear 3D laser scanners, one video camera, one synchronizing controller and four industry computers. Main parameters of main sensors are shown in Table 1. All sensors can work synchronously under GPS time, and acquire such data of ground objects as stereo images, video images, 3D laser point cloud along vehicle running direction. After data post-processing, real geospatial coordinates of ground objects can be obtained from stereo images or laser point cloud. The main work of this paper focuses on data acquisition from vehicle-borne stereo photogrammetry system integrated with GPS, INS and CCD cameras.
Fig.1. The appearance of vehicle-borne mobile mapping system

Table 1 Parameters of main sensors of vehicle-borne mobile mapping system

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Number</th>
<th>Accuracy/Resolution</th>
<th>Frequency</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCD camera</td>
<td>4</td>
<td>1392×1040</td>
<td>1 frame/5 m</td>
<td>UC-1800</td>
</tr>
<tr>
<td>Difference GPS</td>
<td>1</td>
<td>10-40 cm</td>
<td>1 Hz</td>
<td>JAVAD</td>
</tr>
<tr>
<td>INS</td>
<td>1</td>
<td>0.05° (roll, pitch) 0.1° (heading)</td>
<td>200 Hz</td>
<td>iNAV-FMS-1</td>
</tr>
<tr>
<td>Video camera</td>
<td>1</td>
<td>720×576</td>
<td>25 frames/s</td>
<td>JVC 310</td>
</tr>
<tr>
<td>Linear laser scanner</td>
<td>3</td>
<td>0.5° Angle resolution: 0.5°</td>
<td>38 lines/s</td>
<td>SICK LMS 221</td>
</tr>
</tbody>
</table>

The flow diagram of data acquisition and processing based on vehicle-borne mobile mapping system is shown in Fig.2, it is composed of system calibration, data acquisition in outdoor environment, and data post-processing. The system can be applied in such fields as surveying and mapping, updating of city maps, data acquisition and management of road facilities, etc.
3. DESCRIPTION OF THE APPROACH

1.1 3.1 System calibration

To make vehicle-borne mobile mapping system be able to acquire 3D spatial data, the first work is system calibration, including relative calibration and absolute calibration of stereo photogrammetry system. The aim of system calibration is to construct 3D coordinates computation model and work out parameters in this model. The system calibration method of this paper is completed in high accuracy 3D calibration fields (Shown in Fig.3).

(1) Relative calibration

Cameras used in vehicle-borne stereo photogrammetry system are not measurable, and their main focus, internal and external orientation parameters, and aberration parameters are also unknown. To construct relative coordinates computation model of stereo photogrammetry system, the first work is relative calibration. The sketch of confirming position of ground object through homonymous pixels on stereo image is shown in Fig.4. According to the principle of stereo photogrammetry, if conjugate pixel points of ground point in left image and right image are found, and their corresponding pixel coordinates in left image and right image are respectively \((x_1, y_1)\) and \((x_2, y_2)\), relative 3D coordinates computation model for ground point is described as equation (1).
Fig. 4. The sketch of confirming position of ground object through homonymous pixels on stereo image

\[
\begin{bmatrix}
  f_{x1}r_{11} + x_1'r_{31} & f_{x1}r_{12} + x_1'r_{32} & f_{x1}r_{13} + x_1'r_{33} \\
  f_{y1}r_{21} + y_1'r_{31} & f_{y1}r_{22} + y_1'r_{32} & f_{y1}r_{23} + y_1'r_{33} \\
  f_{x2}r_{21} + x_2'r_{31}' & f_{x2}r_{22} + x_2'r_{32}' & f_{x2}r_{23} + x_2'r_{33}' \\
  f_{y2}r_{22} + y_2'r_{32}' & f_{y2}r_{22} + y_2'r_{32}' & f_{y2}r_{22} + y_2'r_{33}'
\end{bmatrix}
\begin{bmatrix}
  X_c \\
  Y_c \\
  Z_c
\end{bmatrix}
\]

(1)

Where,
\[
x' = x - x_0 - k(x - x_0)((x - x_0)^2 + (y - y_0)^2) - p_1(3(x - x_0)^2 + (y - y_0)^2) - 2p_2(x - x_0)(y - y_0) - s_1((x - x_0)^2 + (y - y_0)^2)
\]
\[
y' = y - y_0 - k(y - y_0)((x - x_0)^2 + (y - y_0)^2) - p_2((x - x_0)^2 + 3(y - y_0)^2) - 2p_2(x - x_0)(y - y_0) - s_2((x - x_0)^2 + (y - y_0)^2)
\]

\((X_c, Y_c, Z_c)\) is the relative coordinates of ground point in camera relative coordinate system. \((X_0, Y_0)\) is pixel location of image main point. \(r_{ij}\) (i=1,2,3, j=1,2,3) is element in rotation matrix which represents camera attitude when photographing.

The relative calibration is completed in indoor calibration field. Its main process is described as follows: Firstly, use vehicle-borne system to capture stereo images in calibration field. Secondly, extract pixel coordinates of control points from calibration images. Lastly, according to the mathematical model between pixel coordinates and corresponding ground spatial coordinates, utilize the method of direct linear transformation and nonlinear iteration to work out all kinds of parameters in the model. The detailed description of relative calibration can be seen in reference [14].

(2) Absolute calibration

Coordinate system established by relative is a relative coordinate system. To ensure spatial data acquired by vehicle-borne system having the same benchmark, absolute calibration must be completed after relative calibration. The aim of absolute calibration is to put relative coordinate system into real geospatial coordinate system, and realize direct geo-referencing for vehicle-borne mapping system. Because correlations (rotation and offset) among sensors of vehicle-borne system are fixed, the transformation between relative coordinate system and real geospatial coordinate system can be replaced by transformation between relative coordinate system and INS-carrier coordinate system. The sketch for relation among sensor coordinate systems in vehicle-borne mobile mapping system is shown in Fig.5.
Fig. 5. The sketch for relation among sensor coordinate systems in vehicle-borne mobile mapping system

From the Fig. 5, the direct positioning equation of vehicle-borne mapping system is described as equation (2).

\[
X_w = R^w_{INS} R^c_{INS} X^c_c + R^w_{INS} a^r_{INS} + X^r_{INS}
\]

(2)

Where,

\[
R^w_{INS} = \begin{bmatrix}
a_{11} & a_{12} & a_{13} \\
a_{21} & a_{22} & a_{23} \\
a_{31} & a_{32} & a_{33}
\end{bmatrix} = \begin{bmatrix}
\sin h & \cosh & 0 \\
-\cosh & \sin h & 0 \\
0 & 0 & 1
\end{bmatrix} \begin{bmatrix}
\cos p & 0 & \sin p \\
0 & 1 & 0 \\
0 & \cos p & 0
\end{bmatrix} \begin{bmatrix}
1 & 0 & 0
\end{bmatrix}
\]

\[
a^r_{INS} = \begin{bmatrix}
T_X, T_Y, T_Z \end{bmatrix}^T
\]

and

\[
R^c_{INS} = \begin{bmatrix}
r_{11}, r_{12}, r_{13}; r_{21}, r_{22}, r_{23}; r_{31}, r_{32}, r_{33} \end{bmatrix}^T
\]

are absolute calibration parameters (offset and rotation). \((r, p, h)\) is roll angle, pitch angle and heading angle of INS-carrier when camera photographing. \(X^r_{INS}\) is coordinates of INS-carrier origin in geospatial coordinates system.

The process of working out absolute calibration parameters is described as follows: Firstly, use vehicle-borne system to capture some stereo images in outdoor calibration field. Secondly, use relative coordinates computation model to measure relative coordinates of some control points from stereo images. Lastly, according to relative coordinates and real geospatial coordinates of control points, work out absolute calibration parameters through calibration method based on Roderick matrix. The detailed description of absolute calibration can be seen in reference [13].

1.2 3.2 Stereo image matching method based on epipolar-line constraint

After completing system calibration, if conjugate pixel points of ground point in left image and right image are found, its real 3D geospatial can be computed by equation (1) and (2). On the basis of coordinates computation, other spatial information (length, area, etc) can also be obtained. During spatial information computation, stereo image matching for confirming conjugate pixel points is the key. This paper proposes the stereo image matching method based on epipolar-line constraint and color information, considering the characteristic of fixed correlation between two cameras. This method can quickly and exactly find conjugate pixel points of ground point from stereo images.
The matching similarity measure is the basis of realizing image matching. How to define and calculate matching similarity measure is the principal task of stereo image matching. To improve matching robustness, RGB color information of image is used to compute matching similarity measure. Gray-scale correlation coefficients in red, green and blue channel are respectively computed by equation (3), then the average of these three coefficients is used as colorful matching similarity measure between matching point and searching point.

\[
\rho = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} g_{i,j} g_{i,j} - \left(\sum_{i=1}^{n} \sum_{j=1}^{n} g_{i,j}\right)^2}{n^2} \left(\sum_{i=1}^{n} \sum_{j=1}^{n} g_{i,j}^2 - \left(\sum_{i=1}^{n} \sum_{j=1}^{n} g_{i,j}\right)^2\right) / n^2
\]  

(3)

After defining computation method of matching similarity measure, following work is to confirm searching scope of conjugate point in right image. As conjugate points must be located on conjugate epipolar-lines, epipolar-line can be used as constraint to decrease searching scope. The paper uses relative orientation linear transformation (RLT) algorithm [15], which is based on coplanar equations, to confirm conjugate epipolar-lines during image matching. After epipolar-line parameters \(L_0^i (i = 1, 2, 6, 8)\) are worked out by RLT algorithm, the conjugate point \((x'_i, y'_i)\) on the right image corresponding to the point \((x_i, y_i)\) on the left image can be calculated by the equation (4), where searching scope of \(x'_i\) is from 1 to \(N\) (the size of image is \(M\) rows × \(N\) columns).

\[
y'_i = \frac{(1-L_0^i)y_i - L_0^i x_i - L_0^i x'_i - L_0^i x_i x'_i - L_0^i y_i x'_i}{1 + L_0^i x_i + L_0^i y_i}
\]  

(4)

Therefore, for matching point \((x_i, y_i)\) in left image, stereo matching process of its conjugate point in right image is described as follows. Firstly, according to the equation (4), confirm location of each searching point in the right image. Secondly, compute colorful matching similarity measure between matching point and searching point, and select point with maximal similarity measure as conjugate point.

If there are many matching points in left image, according to continuity constraint, searching scope can be decreased further. For example, point \((x_i, y_i)\) and point \((x_{i+1}, y_{i+1})\) are neighbouring points, and point \((x'_i, y'_i)\) had been matched, its conjugate point is \((x'_i, y'_i)\). Then searching scope of point \((x_{i+1}, y_{i+1})\) in right image is \([x'_q, x'_h] \times [y'_q, y'_h]\), where \(x'_q = x_{i+1} - (abs(x'_i-x_i) + d)\), \(x'_h = x_{i+1} + (abs(x'_i-x_i) + d)\), \(d\) is a given parameter whose value depends on the distortion of the image, and each \(y'_i\) in interval \([y'_q, y'_h]\) corresponding to \(x'_i\) in interval \([x'_q, x'_h]\) can be calculated by equation (4). The sketch of confirming searching scope is shown in Fig.
4. EXPERIMENTS AND DISCUSSIONS

The proposed algorithms are realized with Visual C#.Net, and vehicle-borne data processing software is also developed for verifying validity of vehicle-borne mapping system. Many experiments are completed with real stereo images of natural scenes in Nanjing. These images, whose size is 1392×1040 pixels, are taken by the vehicle-borne mobile photogrammetry system at different time and in different lighting conditions. The appearance of vehicle-borne data processing software is shown in Fig.7. The system calibration results are shown in Fig.8, and Fig.8 (a) is relative calibration result, Fig.8 (b) is absolute calibration result. From calibration results, we can see that our relative accuracy is 3‰, absolute accuracy in X, Y, Z direction are respectively 0.024m, 0.053m, 0.047m.

Except for testing position accuracy of vehicle-borne mapping system with calibration data, the vehicle-borne system was used to acquire spatial data of municipal components in Taizhou city, Jiangsu Province, China. Comparison of data acquired by vehicle-borne system and real data acquired by fundamental surveying was done to test practical accuracy of vehicle-borne system. Practical test for position accuracy of vehicle-borne system is shown in Table 2. The X and Y coordinates in this table are in the Beijing 1954 coordinate system.
Fig. 8. The system calibration results of vehicle-borne mobile mapping system

Table 2 Practical test for position accuracy of vehicle-borne mobile mapping system

<table>
<thead>
<tr>
<th>Point ID</th>
<th>Real $X$ (m)</th>
<th>Real $Y$ (m)</th>
<th>Computed $X$ (m)</th>
<th>Computed $Y$ (m)</th>
<th>$dX$ (m)</th>
<th>$dY$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>491428.105</td>
<td>3594384.581</td>
<td>491427.867</td>
<td>3594384.741</td>
<td>-0.238</td>
<td>0.16</td>
</tr>
<tr>
<td>2</td>
<td>491250.263</td>
<td>3592704.487</td>
<td>491249.957</td>
<td>3592704.878</td>
<td>-0.306</td>
<td>0.391</td>
</tr>
<tr>
<td>3</td>
<td>491128.144</td>
<td>3592017.561</td>
<td>491127.621</td>
<td>3592017.677</td>
<td>-0.523</td>
<td>0.116</td>
</tr>
<tr>
<td>4</td>
<td>491359.988</td>
<td>3595698.276</td>
<td>491359.847</td>
<td>3595697.539</td>
<td>-0.141</td>
<td>0.737</td>
</tr>
<tr>
<td>5</td>
<td>491285.759</td>
<td>3596427.366</td>
<td>491286.246</td>
<td>3596427.724</td>
<td>0.497</td>
<td>0.358</td>
</tr>
<tr>
<td>6</td>
<td>491264.629</td>
<td>3597079.658</td>
<td>491264.964</td>
<td>3597079.645</td>
<td>0.335</td>
<td>-0.013</td>
</tr>
<tr>
<td>7</td>
<td>491241.184</td>
<td>3597513.011</td>
<td>491241.704</td>
<td>3597513.434</td>
<td>0.52</td>
<td>0.423</td>
</tr>
</tbody>
</table>

Fig. 9 shows practical acquisition results of municipal components with vehicle-borne mobile mapping system. Fig. 9 (a) shows tested left images including municipal components, and these municipal components are labeled by lamp symbol. Fig. 9 (b) shows measure results of some municipal components acquired by our data post-processing software.
The left image in Fig.8 (b) is segmented into two binary images Binary-Y and Binary-R by the paper’s self-adaptive image segmentation method. These binary images are shown in Fig.9 (a) and Fig.9 (b). Traffic sign regions confirmed by the gray-value projection and shape analysis are lined out by the rectangles in Fig.9 (c) and Fig.9 (d). The final detected traffic signs in stereo images are shown in Fig.9 (e), results of traffic signs recognition and geometrical information extraction are shown in Fig.9 (f).

Fig.9. Practical acquisition results of municipal components with vehicle-borne mobile mapping system
(b) Spatial data acquisition for municipal components with vehicle-borne data post-processing software

Experimental results show the position accuracy of vehicle-borne mobile mapping system is in the range [0.3-0.8m] when photograph distance less than 50 meters. This accuracy satisfies the demand of municipal components surveying. Experimental results also prove that the validity of proposed calibration methods and stereo image matching method. Therefore, the proposed approach in this paper is not only simple, comprehensible and robust, but also reliable and high-accuracy for data post-processing of vehicle-borne mobile mapping system. The research results of this paper can play an important guidance role on practical engineering application of vehicle-borne mobile mapping system.

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