PRECISION MAPPING OF HIGHWAY LINEAR FEATURES

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ABSTRACT

Direct georeferencing, i.e., direct measurement of the exterior orientation of an imaging sensor by means of integrated GPS/INS continues to generate an increasing interest in the surveying/mapping, and remote sensing communities. The primary driving force behind this process is, on one hand, a need to accommodate the new spatial data sensors, such as LIDAR or SAR (airborne systems), on the other hand, a substantial cost decrease, a possibility of automation of data reduction, and a short turn-around time offered by this technology. The Ohio State University is currently developing a GPS/INS/CCD integrated system for precise (centimeter level) monitoring of highway center and edge lines, sponsored by the Ohio Department of Transportation. The prototype-positioning component of the system is based on a tight GPS/INS coupling, and the imaging component (currently under development) will comprise a single down looking Megaplus ES 1.0/MV Kodak digital camera. This camera is equipped with a powerful 1K by 1K CCD sensor with an image acquisition rate of up to 15 frames per second. The high image rate provides sufficient overlap of the subsequent images, and thus, it will allow for stereo data processing, which, to a large extent, will be done in real-time. The major focus of this paper is the design, calibration, and preliminary performance analysis of the development prototype. The repeatability and consistency tests, based on the vehicle's repeated trajectories, the comparison of the coordinates of the control points extracted from the directly oriented imagery with ground truth, as well as a design architecture of the system, including the real-time image processing module, are presented.

1. INTRODUCTION

1.1 Direct vs Indirect Sensor Orientation

Since the inception of the mobile mapping technology in early 90s (He *et al*., 1994; Bossler and Toth, 1995; El-Sheimy and Schwarz, 1995; Schwarz, 1995), the concept of direct georeferencing and multi-sensor mapping systems has become of increasing interest to the mapping and remote sensing communities, driven primarily by the cost-effectiveness, automation and optimization of data flow, and short turn-around time offered by this technology. Even though an automatic aerial triangulation (AT) has already reached a very mature state, the direct orientation is still advantageous, as it virtually eliminates problems of image matching and need of approximate tie points required for automatic AT to recover exterior orientation. However, a crucial point of application of direct georeferencing is the accuracy and reliability of DPO, depending primarily on sensor quality, stability and accuracy of the system calibration, quality of time synchronization, and the type of the data processing algorithm. DPO is associated with multi-sensor systems, based on the integration of GPS, INS and imaging sensors. A mobile multi-sensor mapping system can be defined as kinematic platform, upon which multiple sensors have been integrated and synchronized to a common time base, to provide three-dimensional near-continuous positioning of both the platform and simultaneously collected geo-spatial data.

Sensor orientation, also called image georeferencing, is defined by a transformation between the image coordinates specified in the camera frame and the mapping reference frame. In traditional airborne surveying, the exterior orientation parameters (EOP) are obtained by AT based on the object space information (control points) and their corresponding image coordinates. As a result of using a mathematical model representing the transformation between the object and image spaces, the EOP are determined, providing a relationship between the local image coordinates and the global mapping reference frame. The combined bundle adjustment usually facilitates not only EOP determination, but may also involve rectification of the camera interior orientation (IO) parameters (pre-determined by laboratory calibration procedure). DPO, however, is usually achieved by inertial navigation or multi-antenna GPS, or, for highest accuracy, by integration of both systems to utilize their complementary features (Grejner-Brzezinska *et al*, 1998). In principle, no external information such as ground control is needed, except for the GPS base station and the boresight calibration range, which is usually needed prior to the mapping mission. The DPO rotational components are naturally related to the INS body frame. Thus, in order to relate the GPS-derived positions, INS-derived attitude components and image point coordinates, a multi-sensor system calibration is required. This procedure must be able to resolve the misalignments between the INS body frame and the imaging sensor frame (boresight transformation), and GPS/INS lever arm with sufficient accuracy. The boresight components are usually determined on a specialized test range, while the linear offsets between the GPS antenna phase center and the center of the INS body frame are precisely measured using traditional surveying techniques. In addition, an imaging sensor must be calibrated to determine the camera interior orientation.

Since contrary to a traditional bundle adjustment, in DPO applications, the IO and EOP estimation processes are decoupled (no common adjustment procedure that could compensate for imprecise IO), it is crucial that the calibration parameters (both IO and boresight) are estimated with high level of accuracy and reliability, and stay constant for the entire mission duration. Another crucial factor is the precise time synchronization usually realized by the exchange of synchronization signals, which relate different sensors to a common time frame provided by GPS. The quality and stability of calibration and time synchronization are especially important for airborne systems, where the object distance is significantly larger as compared to the land-based applications. Any error in IO, timing or boresight components would translate directly into errors in ground coordinates of the extracted objects. For example, the time alignment must be good to at least 0.1msec, if one wants to avoid cm-level and larger errors due to lack of synchronization; 0.1msec translates to 0.6 cm positioning error, assuming 60 m/s aircraft speed. To summarize, the overall performance of the direct orientation method is limited primarily by the following components:

- Quality of the calibration of the integrated system:
  - Imaging sensor modeling
  - Lever arm between INS and GPS antenna
  - Boresight transformation between INS and camera frames
- In-flight variation of the calibration components
- Rigidity of the imaging sensor/INS mount
- Quality of the IMU sensor
- Continuity of the GPS lock
- Kalman filter design

For example, the effects of the boresight quality on the ground object coordinates in the mapping frame can be shown based on the analysis of Equation 1, which is the well-known georeferencing formula. Under the simplified assumptions that all the components, except for the boresight misalignments, are error-free and uncorrelated, the covariance matrix of the object ground coordinates can be obtained by the error propagation formula. Table 1 illustrates an example of the effects of the errors in the boresight components on the object ground coordinates. The average location within a 60 by 60 mm imaging area was selected, with a focal length of 50 mm, and object distance of 20 m and 300 m, respectively; the latitude and longitude were chosen as 40 deg and –81 deg, heading, pitch and roll were selected at 100 deg, 3 deg and 3 deg, respectively for this example (Grejner-Brzezinska, 1999).

Error in boresight offset [m]		**Error in boresight angles [arcsec]**					
		20-m object distance			**300-m object distance**		
		5	10	20	10	20	60
X	0.02	0.02	0.02	0.02	0.02	0.02	0.03
Y	0.02	0.02	0.02	0.02	0.02	0.02	0.05
Z	0.02	0.02	0.02	0.02	0.02	0.02	0.04
X	0.05	0.05	0.05	0.05	0.05	0.05	0.06
Y	0.05	0.05	0.05	0.05	0.05	0.06	0.10
Z	0.05	0.05	0.05	0.05	0.05	0.06	0.10
X	0.10	0.10	0.10	0.10	0.10	0.10	0.11
Y	0.10	0.10	0.10	0.10	0.10	0.10	0.14
Z	0.10	0.10	0.10	0.10	0.10	0.11	0.13

Table 1. Error in object's ground coordinate in [m] due to boresight errors; 20-meter and 300-meter object distance, and focal length of 50 mm were assumed.

$$r_{M,i} = r_{M,INS} + R_{BINS}^{M}\left(s \cdot R_{C}^{BINS} \cdot r_{C,j} + b_{BINS}\right) \quad (1)$$

where :
$r_{M,i}$ $-3D$ *object coordinates in mapping frame*
$r_{M,INS}$ $-3D$ *INS coordinates in mapping frame*
$r_{C,j}$ $-$ *image coordinates of the object in camera frame C*
R_{C}^{BINS} $-$ *boresight matrix between INS body and camera frame C*
R_{BINS}^{M} $-$ *frotation matrix between body and mapping frames*
$s-$ *scaling factor*
b_{INS} $-$ *boresight offset vect*

1.2 Feasibility of Near-Real Time Processing?

Two primary components of a mobile mapping system are precise navigation and digital imaging, both allowing for a flexible and optimal system design, leading potentially to near-real time data processing. From the navigation standpoint, the post processing of GPS/INS data provides more accurate orientation data, benefiting from forward and backward trajectory processing, and precisely synchronized timing information. However, some navigation information available in real-time (such as relative image orientation) can be used to process directly digital stereo-pairs on-the-fly to acquire the information from the images, and store only the needed information, as opposed to the entire image (if only simple features, such as linear objects are needed). The precise on-the-fly time synchronization is one of the most challenging tasks of the real-time image pre-processing. Obviously, further post-processing can rectify the positioning and orientation data that should subsequently be used to provide precise georeferencing to the features extracted in real-time. This procedure adds more robustness to the system, allowing faster and more automatic data processing, saving storage space and processing time, as data acquisition can be combined with the image pre-processing. The following steps, also depicted in Figure 1, describe the concept of real-time and post-processing of digital imagery collected for highway center and edge-line detection. This method is currently being implemented in the mobile mapping system described in Section 2.

1. *Edge detection*
    a. Scattered and unorganized edge pixels
    b. Thresholding to remove noise and to identify larger edge segments
    c. Connecting edge segments
2. *Matching module to extract final line structures*
    a. Feature-based matching (e.g. Ψ-s domain)
    b. Feature-based affine transformation as a first approximation between two consecutive images
    c. Collinearity condition
3. *Tracking/Connectivity between the edge segments based on post-processed DPO*
4. *Line annotation*
5. *Transfer to a GIS database*

2. MAPPING OF HIGHWAY LINEAR FEATURES

The Ohio State University is currently developing a high-accuracy GPS/INS/CCD system for monitoring highway linear features. The system, designed for the Ohio Department of Transportation, is based on the concept of combining real-time and post-processing modules, as presented in the previous section. The positioning component of the system has been completed, and the imaging component (the real-time part) is currently in the implementation stage. In the following sections, a brief description of the system's major modules and the performance analysis of the navigation component are presented. The pilot test, which has demonstrated a successful application of this technology, is also discussed.

2.1 System Design and Architecture

The prototype of the integrated GPS/INS/CCD system (Figure 2) designed for precision monitoring of the highway edge- and centerlines comprises two dual-frequency Trimble 4000SSI GPS receivers, and a medium-accuracy and high-reliability strapdown Litton LN-100 inertial navigation system, based on Zero-lock™ Laser Gyro (ZLG™) and A-4 accelerometer triad (0.8 nmi/h CEP, gyro bias – 0.003°/h, accelerometer bias – 25μg). The LN100 firmware version used in this project allows for access to the raw IMU data, with the update rate up to 256 Hz. Estimation of errors in position, velocity, and attitude, as well as errors in inertial and GPS measurements, is accomplished by a 21-state centralized Kalman filter that processes GPS L1/L2 phase observable in double-differenced mode together with the INS strapdown navigation solution. The estimated standard deviations are at the level of 2-3 cm for position coordinates, and 5-7 arcsec and ~10 arcsec for attitude and heading components, respectively (for extended losses of lock, above 60 s, errors in position can grow to 10-20 cm and more, depending on the gap size).

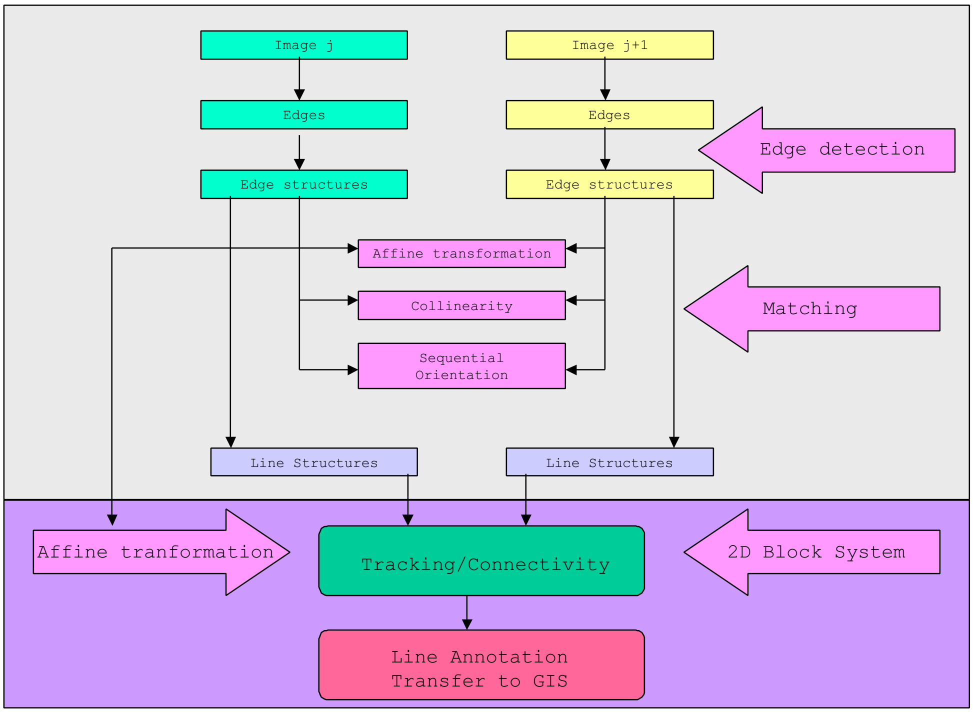

Figure 1. Image processing concept (top block: real-time, lower block: post-processing).

The imaging component in the test configuration consists of a digital camera based on a 4,096 by 4,096 CCD with 60 by 60 mm imaging area (15 micron pixel size), manufactured by Lockheed Martin Fairchild Semiconductors. The imaging sensor is integrated into a camera-back (BigShot™) of a regular Hasselblad 553 ELX camera body, and the camera is installed on a rigid mount together with the INS (Toth, 1998). Due to the low image acquisition rate (6 s) of the BigShot™, the ultimate imaging sensor for the final system will be a Megaplus ES 1.0/MV Kodak digital camera (Figure 3) with 9.07mm by 9.16 mm imaging area (9-micron pixel size) and 15 images per second acquisition rate (15 Hz), which allows for 60% overlap in image acquisition at normal highway speed.

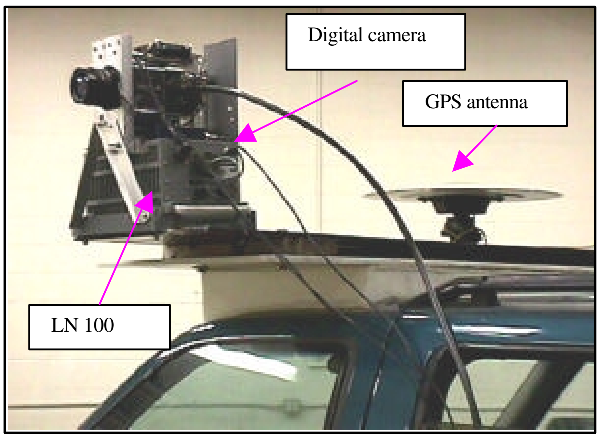

Figure 2. GPS/INS/CCD hardware configuration.

Figure 3. Kodak Megaplus ES 1.0/MV digital camera.

2.2 System Calibration

As indicated in section 1.1, a multi-sensor system calibration is an important factor, which directly impacts the overall quality of DPO parameters. System calibration is defined here as determination of spatial and rotational offsets between the sensors (GPS/INS lever arm and INS/camera boresight components), as well as imaging sensor calibration, since for DPO application the stability and accuracy of the interior orientation parameters of the imaging sensor is mandatory.

For the camera calibration purposes the collinearity equations are extended to include the interior orientation, thus the adjustment procedure produces the calibration results and the 3D coordinates of the object targets, as well as exterior orientation. However, due to correlation among the unknown parameters, the geometry of the entire network must be very strong. This requires 3D set of at least 50 points, and wide range of camera orientations at the exposure times. For the calibration purpose of the BigShot™ 4K×4K CCD with Carl Zeiss Distagon 4/50 50-mm lens, the image coordinate pairs of ~300 points evenly distributed in 3D indoor test range were measured on images acquired from different exposure stations, and subsequently processed with the OSU Bundle-Adjustment with Self-Calibration (BSC) software, providing estimates of the focal length, principal point, and lens distortions. The additional parameters for decentering distortion and the affine transformation for scale differences between axes were constrained to zero for compatibility with the SoftPlotter distortion model. The calibration was repeated independently three times, including also the ~150 point outdoor test range, and the results are presented in Table 2. The results of four independent calibrations indicate that while the distortion model and focal length do not change significantly, the major variation can be observed in the principle point location. This is a natural consequence of the fact that CCD-based camera is not a rigid devise; the camera body and the camera back housing the CCD chip are rather loosely connected, thus any time the camera back is removed and re-attached to the camera body, significant change in the principle point location should be expected, and calibration should be performed. Moreover, the self-calibration during the actual project is advisable, if an adequate test field is available, as it brings the advantage of calibrating under the same conditions as the factual image collection.

Parameter	Calibration 1		Calibration 2		Calibration 3		Calibration 4	
	Value	Sigma	Value	Sigma	Value	Sigma	Value	Sigma
C (mm)	51.568	0.008	51.762	0.008	51.688	0.008	51.570	0.007
Xp (mm)	0.314	0.010	0.669	0.005	-0.075	0.004	0.296	0.004
Yp (mm)	0.112	0.013	0.227	0.005	0.376	0.005	0.073	0.005
Rad1 (K1)	-2.77E-05	9.35E-07	-2.71E-05	3.40E-07	-2.76E-05	2.80E-07	-2.68E-05	4.14E-07
Rad2 (K2)	1.44E-08	5.77E-10	1.38E-08	2.50E-10	1.36E-08	9.30E-09	1.35E-08	3.07E-10

Table 2. 4K by 4K BigShot™ camera equipped with 50-mm lens: calibration parameters

The boresight transformation is most commonly resolved by comparing the GPS/INS positioning/orientation results with an independent AT solution, or as a part of a bundle adjustment with constraints. Thus, the quality of the boresight estimation is limited by the quality of the AT adjustment and the quality of the direct orientation components that are used in the boresight estimation process. Consequently, the availability of a high quality test range with very well signalized points that should be used for the calibration process becomes an important issue. Our practical experiences indicate that even if the control points are surveyed with cm-level accuracy on the ground, their poor signalization (non-symmetric marks, natural targets) may propagate to the projection centers' positioning quality (in the AT process), immediately compromising the boresight performance. For the tests presented here, a specialized test range was used, thus, the AT performance on this range was very high, as presented in Table 3. Since the GPS/INS also provided quality solution (see section 3), the resulting boresight parameters were of good quality, with RMS of 2-3 cm for offsets, 15-20 arc sec for angular components, which based on Table 1, should introduce positioning error no bigger than 2 cm even for very long object distance.

Point ID	E [m]	N [m]	H [m]	E residual [m]	N residual [m]	H residual [m]
14	553789.008	221908.411	212.473	-0.003	-0.001	0.002
15	553789.426	221909.427	212.448	-0.006	0.002	0.000
24	553788.985	221908.418	211.366	0.010	0.000	-0.002
25	553789.407	221909.438	211.356	0.009	-0.002	-0.001
34	553788.974	221908.415	210.272	-0.006	0.002	0.001
35	553789.390	221909.437	210.248	-0.004	0.000	0.000
RMS				0.007		0.001

Table 3. AT performance on the boresight range.

3. Test Data and Navigation Performance Analysis

For the tests presented here, a side-looking Hasselblad camera with BigShot™ CCD sensor and 50-mm focal length, as described in Section 2.1, was tilted downwards by 5°, and mounted rigidly on the top of the LN100, offset from the GPS antenna by ~1 m. The imagery was collected along the surveyed road, and the subsequent stereo-pairs (formed by the time-offset succeeding images) were formed with the directly acquired orientation parameters. The effective ground pixel size was ~2-4 mm at the target area. The position standard deviations, the number of satellites tracked and the RDOP are presented in Figure 4 for the entire test duration. The standard deviations for pitch and roll were at 5-8 arcsec level, while heading standard deviation ranged between 8-12 arcsec, depending primarily on vehicle dynamics. The spikes that can be observed in the position standard deviation plot correspond to partial or total losses of GPS lock when the vehicle was passing under the foliage or close to the buildings. The otherwise low level of the standard deviations indicates the quality solution, but an independent check is always needed to assess the system's absolute accuracy, which is usually accomplished by an independent photogrammetric solution or the comparison of the control point coordinates with their counterparts extracted from the directly oriented imagery.

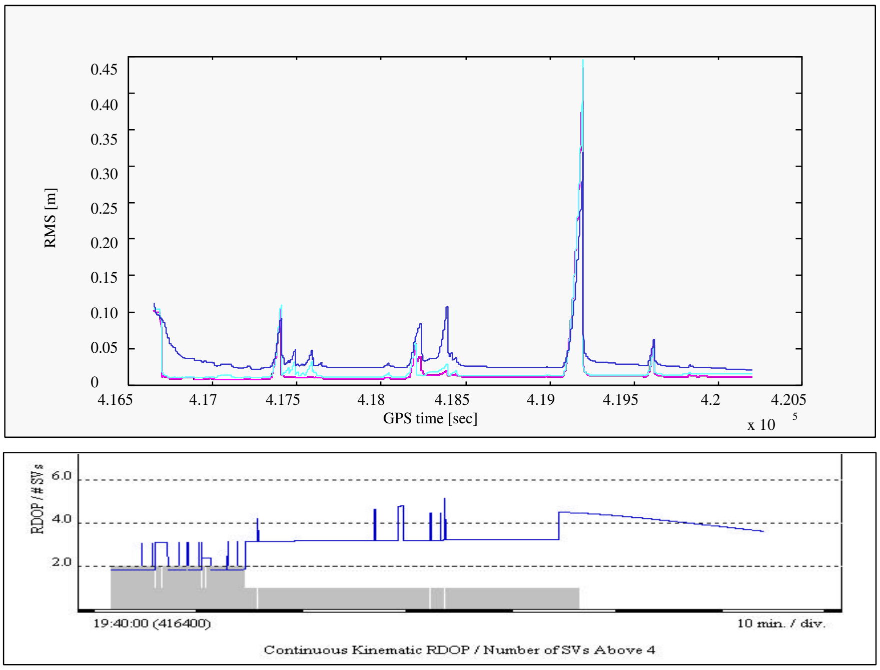

Figure 4. Position standard deviation and satellite observability for the entire test duration.

3.1 Absolute Positioning Accuracy

The overall accuracy measure can also be achieved by examining the repeatability of the solution obtained for the check points measured on different directly oriented stereo pairs. The statistics of such a comparison, based on over 40 stereo pairs, is presented in Table 4. The results indicate that the direct orientation parameters were indeed estimated with high quality. Another repeatability test was performed by comparing the ground coordinates of 15 check points measured on the directly oriented stereo pairs from two different passes (the entire test trajectory consisted of 2 repeated tracks), also shown in Table 4. The GPS/INS/image data for those passes were collected with slightly different GPS constellation; the pass one observed six satellites, whereas pass two was able to collect GPS data from five and less satellites (see Figure 4 for satellite observability). This is reflected in the differences in the positions listed in Table 1 (Grejner-Brzezinska, 1999).

The ultimate accuracy test for the direct orientation derived from GPS/INS after the boresight was applied, is the comparison of the ground coordinates obtained by the photogrammetric methods based on the directly oriented imagery, and the ground coordinates of the GPS-determined control points. The control points used in this test were determined with accuracy of ~1.5 cm per coordinate. They were located ~18 m from the perspective center of the camera, when the directly oriented imagery was collected. The comparison performed on 4 control points is presented in Table 5 (Grejner-Brzezinska, 1999).

Statistic	Easting [m]	Northing [m]	Height [m]	Statistic	Easting [m]	Northing [m]	Height [m]
Mean	0.015	0.004	0.008	Mean	0.015	0.014	0.044
Median	0.006	0.003	0.006	Median	0.013	0.011	0.045
Maximum	0.050	0.025	0.035	Maximum	0.050	0.034	0.130
RMS	0.019	0.007	0.010	RMS	0.020	0.018	0.052

Table 4. Ground coordinate difference for the check points measured from different stereo pairs (left side of the table) and for 15 check points measured on stereo pairs from overlapping passes (right side of the table).

Point	Object distance	Easting [m]	Northing [m]	Height [m]
1	17.25	0.002	0.029	0.008
2	16.30	0.009	0.015	0.000
3	18.57	-0.019	0.029	0.010
4	17.86	-0.059	0.018	0.009
RMS		0.031	0.007	0.005

Table 5. Coordinate difference between control points measured on the imagery and the ground truth.

3.2 Image Processing: A Concept

The real-time image pre-processing is designed according to the scheme presented in Section 1.2, and is practically feasible due to a simple sensor assembly, and the limited complexity of the imagery collected. Since the consecutive image pairs are acquired by a single down-looking camera, they cover only the road surface to the side of the vehicle, therefore the object contents of the images are rather predictable. For example, the surface is flat, the road edges are parallel to the driving direction, and the road edges are usually defined by a solid or dashed bright line. Based on these rules, the feature extraction (in our case center and edge lines only) can be easier and more reliable. Consequently, the edge detection algorithm would search for a sudden change in the gray values in the direction perpendicular to the driving direction. This procedure is expected to be performed on-the-fly (as explained in Section 1.2), and would provide a binary image showing only the bright linear features of the road. Then, the thinned and vectorized polylines would be approximated by straight lines, whose precise coordinates would be obtained in post-processing, based on the final GPS/INS solution and transformation parameters determined by the calibration procedure.

The ultimate positioning accuracy of the lines extracted from the directly georeferenced imagery depends on the quality of DPO and the imaging component, time synchronization (see Section 1.1), multi-sensor calibration, as well as the accuracy of the edge extraction procedure. The accuracy range of the imaging system is determined by the resolving power of the imaging sensor, the base length, the quality of the camera calibration, and the depth range of the application. The importance of these components is briefly addressed in the sequel.

The practically achievable accuracy of DPO in the system presented here ranges between 1-4 cm in positioning and 6-10 arcsec in attitude provided favorable GPS constellation, and no extended losses of lock. Since the object distance is very short (in the final hardware implementation, it will be about 2 m), the possible inaccuracies in boresight angular offsets should not affect the final coordinates, even if they reach 1 arcmin or more (see Table 1 for more reference). The linear offset errors, though, will translate directly into the ground coordinates (see Table 1); however, the practically achievable boresight accuracy is at the cm-level, provided that specialized range is available.

Naturally any error in IO will directly affect the ground coordinates, however, our calibration experiences indicated that all components, including the radial distortion parameters can be determined with high accuracy on a specialized target range, and the remaining mis-calibration error should not exceed the sub-pixel level (see Table 2). With 2-meter object distance and 9-µ pixel size (corresponding to a 2-mm pixel size on the ground if 10 mm lens is used) the effects of calibration errors can be neglected. Similarly, the error related to the automatic edge extraction procedure can reach a few pixels, depending on the type of algorithm used. However, in the scenario presented here, even 5-pixel error would cause only a 1-cm error on the ground. Thus, under the circumstances discussed above, the major component contributing to the ground coordinate error is the accuracy level of DPO (provided that calibration components do not change during the mapping mission, which is a very likely scenario, as land-based applications have more controllable environment, as compared to airborne cases).

One more issue related to the geometry of the imagery collected by a single camera, where stereovision is achieved by the platform motion, is the base to depth ratio. In our case, assuming the speed of about 60 km/s, and image collection rate of 15 Hz, the base would be close to a meter. Thus the effective base/depth ratio is about 1:2, which provides quite favorable conditions. Earlier OSU experiences with GPSVan™ (He et al, 1994) indicate that a 1K by 1K CCD sensor with about 2-m camera base results in positioning accuracy better than 3 cm for object distances of 5 m (ratio of 1:2.5) and growing to 15 cm for 25 m (ratio of 1:12.5), respectively.

5. SUMMARY

The test results presented in this paper indicate that an integrated land-based system supported by a medium to high quality strapdown INS and dual frequency differential GPS offers a capability for automatic and direct sensor orientation with high accuracy, offering options of near-real time image preprocessing. The crucial factors limiting the DPO quality are the accuracy and stability of multi-sensor system calibration and the camera IO. Accurate and invariable boresight transformation, precise time synchronization and precise estimation of the IO parameters are the most important calibration components, impacting the overall accuracy of DPO and the object space coordinates. Any error in IO will directly affect the ground coordinates, as DPO provides no compensation for erroneous or imprecise IO, as opposed to a bundle adjustment. From this stand point, the integration of GPS/INS into a combined AT might provide the best and most reliable solution, as camera calibration (self-calibration) could be a part of the combined adjustment. Since GPS/INS provide high quality positioning information, the AT process, in principle, would require much less tie points as opposed to AT with no GPS/INS, to correct IO and exterior orientation. Moreover, such a combined procedure would allow for independent boresight estimation based on the image data collected during the actual survey. These issues are more relevant to airborne systems, where the object distance is much bigger than that of the land-based system, where GPS/INS with carefully calibrated camera and boresight/lever arm is capable of providing high accuracy and reliable DPO (on one hand it is more controllable environment, on the other hand, more GPS losses of lock can occur as opposed to airborne scenario). Nevertheless, the testing against the ground truth should be performed occasionally also for the land-based systems, to assure that no change in calibration components/system configuration, which would impact the DPO estimates, occurred.

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