BRIDGING LAND-BASED MOBILE MAPPING USING PHOTOGRAMMETRIC ADJUSTMENTS

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ABSTRACT:

The increasing demand for up-to-date 3-D geographic information systems (GIS) in planning, transportation, and utility management applications poses significant challenges to the Geomatics community. Of all the challenges in acquiring, building, maintaining, and using GIS, none is more central than that of data acquisition. Obtaining the required spatial and attribute data by conventional methods such as aerial photogrammetry and terrestrial surveying is expensive, slow, or inaccurate. These methods are, therefore, not well suited for rapid updating. Fortunately, however, the development of land-based mobile mapping systems (MMS) has opened a new avenue to meet these challenges. Land-based MMS are capable of providing fast, efficient, cost-effective and complete data acquisition. As such, they are an innovative technology for creating and updating 3-D GIS databases both quickly and inexpensively.

Basically, MMS are based on integrated navigation systems, mainly the integration of GPS and inertial sensors. The integration of these two technologies results in navigation systems with extremely accurate velocity, position, and attitude with almost no noise or time lags. Under ideal conditions, the GPS measurements are consistent in accuracy and availability throughout the survey mission. However, for land-based MMS, such conditions do not often exist. This is especially prevalent in urban centres and when encountering highway overpasses or tunnels. The overall objective of this paper is investigating a purely photogrammetric strategy for georeferencing of short image sequences as backup system when the navigation solution is not available or not sufficiently accurate, a typical case during GPS signal outage periods. A photogrammetric strategy for the georeferencing of image sequences acquired by MMS is presented. These objectives are accomplished through the simulation of the University of Calgary VISAT (Video, Inertial, and SATellite GPS) mobile mapping system.

1. INTRODUCTION

A mobile mapping system (MMS) can be defined as the product that integrates the concepts of kinematic geodesy, aerospace engineering, automatic control, remote sensing, and digital photogrammetry, to acquire, store, and process measurable quantities that sufficiently describe spatial and/or physical characteristics of a part of the Earth's surface (Mostafa, 2003). Thus, MMS can provide a complete mapping solution with data acquired from only one platform. The idea of mobile mapping, i.e. mapping from moving vehicles, has been around for at least as long as photogrammetry has been practiced. The early development of mobile mapping systems was, however restricted to applications that permitted the determination of the elements of exterior orientation from existing ground control. However, technological advancement in positioning/navigation and imaging sensors that occurred during the last decade of the twentieth century substantially refined the concept of airborne and land-based mapping. The advent of the first mobile mapping system in the early 1990s initiated the process of establishing modern, fully digital, virtually ground control-free photogrammetry and mapping, which considerably enhanced both the efficiency, the flexibility and the cost (after Schwarz and El-Sheimy, 2004).

The overall accuracy of mobile mapping system depends largely on the accuracy of the navigation devices and their integrated solution. The navigation system invariably includes GPS. Unfortunately, GPS signals are not often available for computation of position all the times in urban areas. Thus, it is important to understand the accuracy of mobile mapping systems in such situations where the GPS signals are obstructed, and also to investigate methods of overcoming the problem. In this paper the concept mobile mapping is briefly introduced. Problems associated with using the MMS in urban centres are then discussed. The concept of photogrammetric bridging as an alternative method for navigation during GPS signal outage periods is illustrated. Data preparation and testing are discussed as well as the obtained results and finally conclusions are drawn.

2. PRINCIPLES OF LAND BASED MOBILE MAPPING SYSTEM

The components of any land-based MMS are divided into two major types of sensors: the navigation sensors and the mapping sensors. The navigation sensors in the carrier platform (typically a van) are used to determine the platform trajectory during the surveying mission. The mapping sensors (typically digital cameras) are used to determine the positions of the object points relative to it.

Basically, to georeference mapping sensors, the parameters of interior and exterior orientation have to be determined. The interior orientation parameters can be estimated through the camera calibration process. These parameters are considered more or less constant over a period of time (Grejner-

Bezezinska, 1999). In contrast, the six parameters of camera exterior parameters are changing quickly as the platform moves, and their evolvement has to be tracked to achieve georeferencing without the slow and costly establishment of ground control networks

The implementation of the direct georeferencing concept is an inertial navigation system (INS), which typically consists of three gyroscopes to sense the angular velocities and three accelerometers to sense the specific force resulting from the body's linear motion. By integrating the first set of measurements with respect to time, orientation changes of the platform with respect to the mapping frame can be obtained. On the other hand, the position vector of the platform in the mapping frame can be obtained by double integrating the sensed specific forces after being transformed to the navigation frame. Thus, an INS can, in principle, provide all information needed for this specific application. Inertial measurements are characterized by their high data rate and high short term stability. However, due to the double integration, the time-dependent position error will quickly accumulate. Frequent updates are, therefore, needed to achieve the required system accuracy. On the other hand, GPS is another measuring system that can be used in kinematic positioning. Cycle slips cause a discontinuity in the trajectory. In addition, the GPS data rates are not sufficient to meet the requirements of many applications, including terrestrial MMS.

The integration of GPS/INS, therefore, offers a number of advantages. In the absence of cycle slips, the excellent positioning accuracy of differential GPS can be used to provide frequent update for the INS. The INS orientation information and precise position and velocity facilitate cycle slip detection and correction. In general, the fact that nine independent measurements (3 linear accelerations, 3 angular velocities, and 3 GPS coordinates updates) are available for the six required trajectory parameters greatly enhances the reliability of the trajectory determination of the mobile mapping system.

After the trajectory of the carrying vehicle has been accurately described by the time variable navigation solution, the cameras' positions and attitudes have to be interpolated based on the estimated trajectory information, taking into account both the spatial and temporal offsets between the camera and the INS.

Following the georeferencing step, mapping of features of interest takes place. This step can be achieved through a simple intersection process by tracing the mapped featured in at least two georeferencing images (either synchronized or asynchronized images). The epipolar geometry plays an important role in speeding up the mapping process, especially with linear features that are not aligned with the epipolar line where singularity might exists.

It should be emphasised here that, contrary to airborne applications, position georeferencing errors have a larger effect on the object space reconstruction than that of angular errors. This is due to the fact that the object distance is rather small: 10-30m. A 10cm position error, for example, will yield to equivalent error in the object space while 10' error will cause an error in the object space with magnitude about 8cm at 30m object distance.

3. DIRECT GEOREFERENCING MATHEMATICAL MODEL

The formulation of the direct geo-referencing formula is rather straight-forward. Figure 1 shows a schematic of a land-based mobile mapping using a digital frame camera as well as the involved coordinate frames. Equation 1 is the basic mathematical model for the mapping process for mobile mapping systems either being aerial or land-based.

$$\mathbf{r}_i^m = \mathbf{r}_{INS/GPS}^m(t) + \mathbf{R}_b^m(t)\left[s^i \mathbf{R}_c^b \mathbf{r}^c + \mathbf{a}_c^b \right] \qquad (1)$$

Where

$\mathbf{r}_i^m$	is the 3-D coordinate vector of point (i) in the mapping frame (m-frame)
$\mathbf{r}_{INS/GPS}^m(t)$	is the interpolated coordinate vector of the navigation sensors (INS/GPS) in the m-frame
s^i	is the scale factor corresponding to point (i)
$\mathbf{R}_b^m(t)$	is the interpolated rotation matrix between the navigation sensor body frame (b-frame) and the m-frame
(t)	is the time of image capture
$\mathbf{R}_c^b$	is the rotation matrix which represents the misalignment between the camera and the body frames, determined by calibration
$\mathbf{r}^c$	is the image coordinate measurement vector
$\mathbf{a}_c^b$	is linear offset between the camera and the body frames, determined by calibration

The georeferencing formula (Equation 1) contains four unknowns (3 coordinates and one scale factor) in three equations. Having a second image of the same scene will add three extra equations and one unknown (scale factor) for the same point (i). A least squares solution of the space intersection between the two rays from the two georeferenced images can then be implemented to estimate the 5 unknown. A detailed discussion of implementation aspects can be found in El-Sheimy (1996).

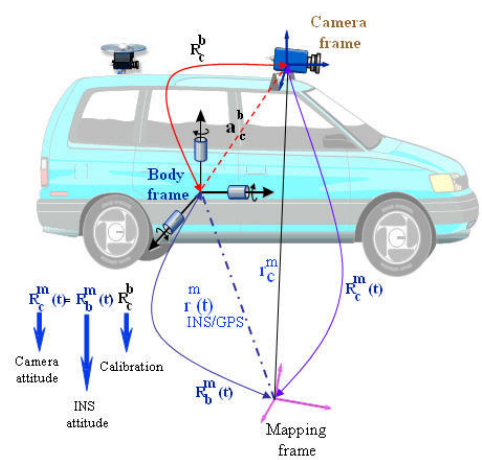

Figure 1: Relation between Coordinate Frames in Land-Based Mobile Mapping Systems

Additionally, it is can be observed from equation 1 that the overall performance of such system depends on the accuracy of the navigation state (i.e. integrated GPS/INS output), the calibration of the spatial and temporal offsets between the navigation and mapping sensor, and the quality of the image measurements. In this work, the first element is considered.

More details on the total system calibration can be found in Grejner-Brzezinska and et. al. (2002).

As a stand-alone dead-reckoning system, the INS experiences time-dependant drifts due to the integration of uncompensated inertial sensor errors. Thus, the INS needs to be updated frequently by another aiding system of white noise spectrum or reference signal (e.g. GPS). The updates are direct measurements of one or more elements of the navigation state, such as position, velocity or attitude depending on the utilized aiding sensor. The GPS provides coordinate updates (CUPTs) and velocity updates. The updates are implemented through Kalman filter which evaluates the INS errors by comparing the output of the INS mechanization with the GPS reference signal. By considering the difference in the signal as an error of the INS, the INS errors can be estimated and subtracted from the original INS navigation solution.

Another source of updates is zero velocity updates (ZUPTs). As their name suggests, ZUPTs are accomplished by stopping the vehicle at a regular basis, depending on the INS grade, for 10-20secs. In this case, the velocity reference signal is null, and the Kalman filter re-initialize the velocity vector to zero and thereby correct for accumulated INS velocity drift. Unfortunately, stopping the vehicle is not always possible, especially in urban areas where the traffic flow would be interrupted. Further improvements in position and azimuth accuracy can be achieved if an odometer is added for velocity aiding or a multi-antenna GPS is used for azimuth control.

Figure 2 shows a typical MEMS-based INS (with Gyro Bias instability "during 100 seconds" of 0.01 deg/seconds) error behaviour during a series of simulated 10 second GPS signal outages. The MEMS INS (developed by the University of Calgary) data with simulated GPS signal outages was processed and the results were compared to the reference solution. The average position error at the end of outages is 6m, which does not meet the accuracy requirement for virtually any mobile mapping application. Figure 3 shows the error behaviour of the same INS after applying Non-Holonomic Constraints (NHCs) and Odometer Derived-Velocities (ODV) as update measurements using the University of Calgary's AINS™ software, an Aided Inertial Navigation System Toolbox for MatLab® (Shin and El-Sheimy 2004).

The accuracies achieved with many land MMS systems, such as the VISAT system (El-Sheimy, 1996), are suitable for all but the most demanding cadastral and engineering applications. Accuracies in this case mainly depend on availability of GPS signals and how long the INS systems can work independently in stand-alone mode. If GPS is available, the positioning accuracy is uniform at a level of 3-5 cm (RMS). If GPS is not available, the positional accuracy depends on the duration of the GPS signal outage.

4. RELATED WORK ON BRIDGING GPS OUTAGES

Based on the previous discussion, the accuracy of a mobile mapping system depends on the accuracy and continuity of the aiding source data and most specifically GPS. Unfortunately, although GPS can provide highly accurate positions in ideal conditions, as a stand-alone navigation system it is known to have certain limitations in urban areas (e.g. city centres), under heavy tree or forest canopies, and inside tunnels. In such situations, the GPS signals are blocked, and thus, navigation is totally lost until signals are reacquired. This will result in very poor positioning accuracy especially in kinematic navigation or when such signal blockage periods reach several minutes.

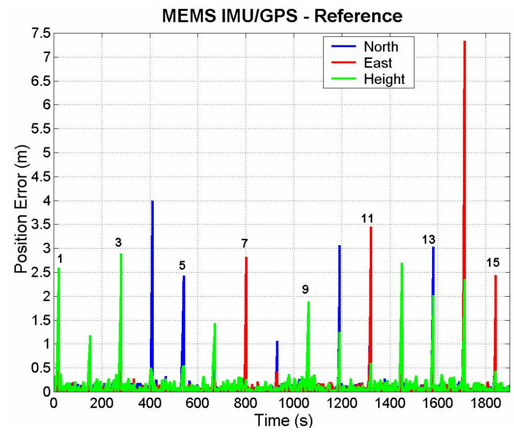

Figure 2: MEMS INS Position Errors during 10 secs GPS Signal Outages

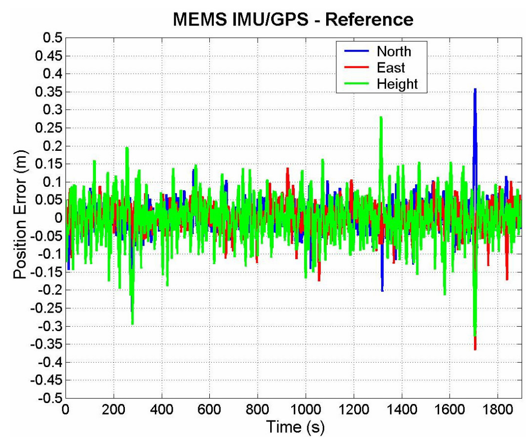

Figure 3: MEMS INS Position Errors during 10 secs GPS Signal Outages After Applying NHCs and ODV Updates

Moreover, in these areas, ZUPTs are also not applicable due to traffic conditions.

GPS data is typically included in the photogrammetric adjustment as externally-processed position observations. However, Ellum and El-Sheimy (2005) have proposed a more fundamental fusion of the GPS data in the same adjustment as the image measurements. In other words, measurement-level integration of the navigation and photogrammetric data-streams. This enables GPS data to be used when less than four satellites are visible, which could be beneficial for terrestrial mobile mapping systems.

Forlani, Roncella, and Remondino (2005) have presented a pure photogrammetric strategy for automatic orientation of short image synchronized sequences. They used the structure and motion reconstruction technique to extract and match conjugate points. After the matching process the mismatches are removed by robust estimation of the fundamental matrix and trifocal tensor. The extracted points are introduced to the bundle adjustment to compute the final point coordinates and the orientation parameters. The authors, however, experienced instability of the bundle adjustment due to poor imaging geometry. The accuracy of the estimation, as represented by RMSE, of the navigation solution is below 50cm for the projection centres and 2.4° for the attitude.

Bayoud, Skaloud, and Merminod (2004) implemented a GPS-independent mobile navigation and mapping technique. Their system employs the photogrammetric intersection to determine the object coordinates of surrounding features. Then, after the platform has moved, new sensor orientations are computed using photogrammetric resection with the object co-ordinates computed at the previous position. The positions and attitudes output by the resection are then used as external measurements in an INS Kalman filter to compute the enhanced exterior orientation parameters required for the next intersection process.

Chaplin (1999) proposed an image based bridging strategy, which enables the estimation of the three dimensional motion parameters of a mobile mapping system from the sequence of time-varying imagery which operates in the absence of the GPS/INS data. In this context, he developed a semi-automatic strategy for determining the exposure station exterior orientation parameters based on the principles of digital photogrammetry and computer vision.

4. PHOTOGRAMMETRIC BRIDGING

Mobile mapping systems are designed to capture different data types, such as images, 3-D point clouds, and information from the surrounding environment, with an operating speed in the range of 50-80km/h. As stated earlier, continuous and consistent trajectory data is achieved through the GPS/INS integration using a Kalman filter. The images are, then, georeferenced by interpolating the positions and attitudes at the time of exposure based on GPS time synchronization and taking into account the spatial offsets between the navigation and imaging sensors. It was previously explained that the INS derived positions will drift during GPS signal outages or to a lasting poor satellite visibility.

In this paper, instead of relying on the navigation sensors to provide the position and attitude information, a photogrammetric bridging procedure is used. In this procedure, an adjustment is done using image measurements of tie points tracked through successive frames. In order to remove the datum deficiency, the position and attitude of the first and last exposures in the sequence, where the navigation solution is reliable, are together introduced to the bundle adjustment as parameter observations. Where the GPS/INS derived navigation information, either through loosely or tightly coupled integration, can be used in photogrammetric network adjustment with their appropriate weights as extracted from Kalman filter covariance information.

5. DATA PREPARATION AND TESTING

To achieve the objective of this paper, a photogrammetric network was simulated based on a pre-specified 3-D object space and vehicle trajectory. Figure 4 shows the cross-section of the trajectory, which was intended to mimic a typical urban imaging geometry. Since the angle of the intersection of the light rays at the tie points has a great effect on the photogrammetric network geometry and consequently on both the reconstruction process and the stability of the bundle adjustment. Therefore, the tie points are simulated only on the side buildings which will give better angle of intersection than those on the road surface. The elevations of the simulated 3-D object space points are 0m, 3m, and 5m. The simulated tie points are based on the careful study of the camera coverage.

The simulated trajectory is selected to be a straight line, as is the case for most urban streets in North America. The simulated exposure stations are separated by 10m along the road centre line. The van is assumed to move on a flat horizontal road (Z≈0). Using the simulated vehicle positions and attitudes together with the generated control field, the adjustment/simulation software developed in Ellum and El-Sheimy (2005) was used to simulate image measurements. The simulated camera system corresponds to that of the real VISAT mobile-mapping system.

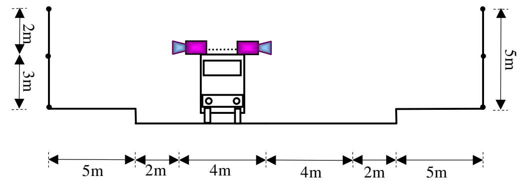

Figure 4: X-Section of the Simulated Control Field on the Left and Right Buildings.

The VISAT system consists of 8 cameras located in two enclosures (4 cameras each). Figure 5 shows a top view of the cameras distribution in one of the enclosures. Only a single camera enclosure is shown and it is symmetric about the motion direction. The simulated camera corresponds to the real Kodak KAI-2020 camera. The camera has a 1600×1200pixel CCD array, and a pixel size of 7.4 microns. The camera focal length is 1700 microns. The base distance between the two camera enclosures is 2 metres.

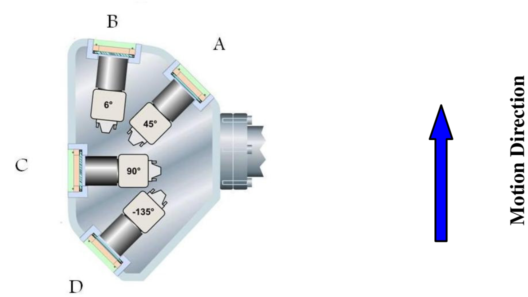

Figure 5: VISAT Imaging System (Single Enclosure)

The required back-projection is done using the collinearity equations, taking into account the attitude and lever-arm offsets of the cameras with respect to the INS body frame. Normally-distributed random noise with a standard deviation of 0.5pixel was added to the simulated image measurements.

Based on the simulated image measurements, and fixing only the exterior orientation parameters of the first and the last exposure in the trajectory, the terrestrial photogrammetric network was adjusted simultaneously. The output of the adjustment is the object space coordinates of the tie points which can be used to evaluate the reconstruction of the object space using the photogrammetric reconstruction principles only. In addition, the exterior orientation parameters of the exposures are also computed.

It should be noted here that the main objective of this work is the georeferencing of the images taken by the MMS during the GPS signal outage. For this reason, the evaluation of the accuracy will be based on the recovered orientation parameters rather than on the reconstructed object space. The conclusions either on the reconstructed object space or on the recovered trajectory should, in principle, agree – provided that a good interior orientation parameters of the camera have been estimated. This can be explained that in case of indirect georeferencing (as the case here), errors in the interior orientation parameters are absorbed by the exterior orientation yielding to a good estimation of the object space.

In the first simulation, the distance between the simulated tie points is 5m along the road centreline and the length of the GPS outage was 200m. Image measurements were simulated for all exposures captured from all cameras along the trajectory. Thus, the simulated network had very good connectivity and, consequently, yielded high accuracy for both the 3-D trajectory and the reconstructed object space. The error was at the mm-level for the both the reconstructed object space and the exposure positions and in the order of 10 arc seconds for the exposure attitudes.

In order to make the use of photogrammetric bridging in case of GPS signal outage more realistic, the amount of human interaction required should be considered. Automatic tracking of points along terrestrial image sequences is a complex task due to large variation in image scale, moving objects and complex modelling of the parallax field (Forlani, Roncella, and Remondino, 2005). Consequently, much manual measuring of points is still required. In the previous simulation, the total number of image measurements was 2600 with, on average, 17 image measurements per image. The obtained accuracy was very high, but making so many image measurements seems to be not realistic. To reduce the image measurement requirements, additional simulations were performed with different configurations that did involve all the cameras. Figure 6 shows the tested configurations and Table 1 presents the statistics as obtained by comparing the reconstructed trajectory and the simulated one.

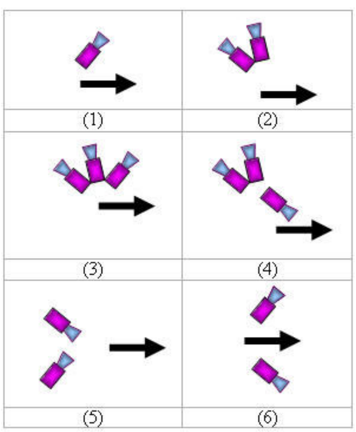

Figure 6: Tested Configurations

Using configuration 5, another test was performed where the distance between the tie points was increased to 10m. This reduces the number of image measurements to 400. The obtained accuracy of the reconstructed trajectory in this case is 27mm, 36mm, and 24mm for x, y, and z, respectively and 65, 89, and 113 arc seconds for roll, pitch, and yaw, respectively. This test was repeated where the tie points in the middle of images that have elevation of 3m are removed. The total number of image measurements in this case is 266 measurements, with 7 measurements/image. The RMSE of the reconstructed trajectory was 15mm, 41mm, and 21mm for x, y, and z, respectively, and 33, 137, and 231 arc seconds for roll, pitch, and yaw, respectively. In such experiment a point should be tracked in 3.5 successive images. Figures 7a and 7b show the quality of the reconstructed trajectory in such case as well as the number of image measurements required in each configuration.

		Position error (m)			Attitude error (")			Image measurements	
		x	y	z	roll	pitch	yaw	Average	Total
1	Min.	-0.034	-0.218	-0.065	-1677	-160	-781	18	342
	Max.	0.429	0.045	0.065	854	249	875		
	Mean	0.186	-0.077	0.000	-388	20	32		
	RMSE	**0.142**	**0.085**	**0.041**	**725**	**128**	**439**		
2	Min.	-0.085	-0.029	-0.015	-968	-42	-227	12	456
	Max.	0.016	0.029	0.065	75	74	108		
	Mean	-0.026	0.000	0.016	-282	20	-32		
	RMSE	**0.029**	**0.016**	**0.024**	**322**	**31**	**78**		
3	Min.	-0.026	-0.013	-0.021	-393	-37	-45	14	798
	Max.	0.004	0.001	0.028	397	33	83		
	Mean	-0.015	-0.006	-0.002	85	4	19		
	RMSE	**0.010**	**0.004**	**0.012**	**200**	**21**	**33**		
4	Min.	-0.010	-0.005	-0.017	-37	-28	-68	13	742
	Max.	0.055	0.013	0.014	127	87	62		
	Mean	0.018	0.003	-0.003	26	32	7		
	RMSE	**0.021**	**0.005**	**0.011**	**41**	**30**	**41**		
5	Min.	0.000	-0.057	-0.044	-48	-271	-287	18	684
	Max.	0.183	0.049	0.045	32	89	294		
	Mean	0.107	-0.008	0.003	-2	-70	-52		
	RMSE	**0.060**	**0.035**	**0.034**	**27**	**116**	**155**		
6	Min.	-0.817	-0.057	-0.018	-97	-76	-680	12	512
	Max.	0.000	0.157	0.037	20	162	751		
	Mean	-0.432	0.069	0.008	-31	43	103		
	RMSE	**0.299**	**0.070**	**0.019**	**36**	**73**	**407**		

Table 1: Statistics of the Differences between the Reconstructed and Simulated Trajectories using the Configurations in Figure 6.

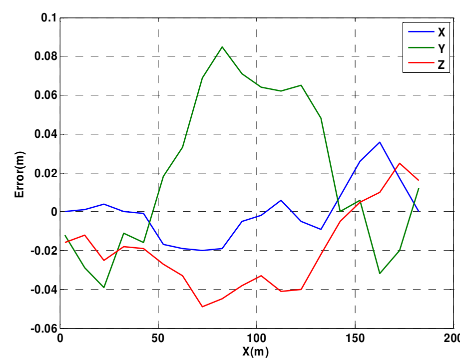

Figure 7a: Accuracy of the Camera Position along the Trajectory

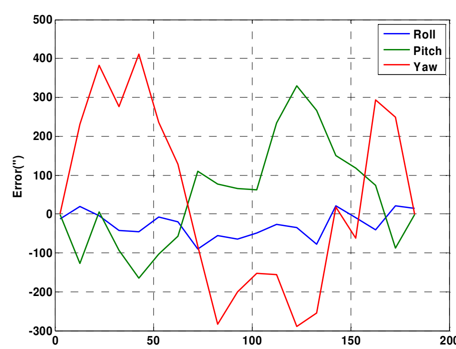

Figure 7b: Accuracy of the Camera Attitude along the Trajectory

After the recovery of the attitude and projection centres of the involved cameras, the rest of the system cameras can be georeferenced based on the boresight angles and lever-arm offset for each camera. Accordingly, it is important to have the proper boresight calibration parameters.

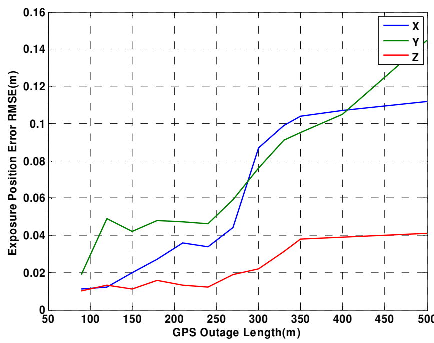

Figure 8a: RMSE of the Exposure Positions with Variable GPS Outage Length

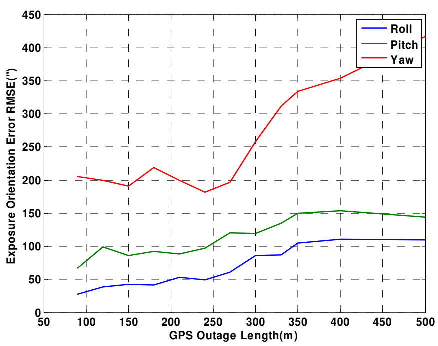

Figure 8b: RMSE of the Exposure Attitude with Variable GPS Outage Length

Based on the previous test configurations the GPS signal outage length was varied to study the error in the reconstructed trajectory versus the GPS signal outage length. Figures 8a and 8b show such results.

Figures 8a and 8b clearly indicate that as far the attitude angles are concerned, the solution for the roll angles and pitch are better than those for the yaw (azimuth) angle. The estimation of the elevations is better than those for the horizontal positions of the camera exposure. It was also noticed that providing the attitude of the last exposure does not alter the results while providing the position of the last exposure is a must. For the GPS signal outage length of 500m (equivalent to 30 seconds interval for a vehicle travelling at 60km/h), the corresponding accuracy for the reconstructed object space is in the order of 25cm (RMSE) which is comparable to the accuracy obtained by VISAT system in normal operational conditions.

6. CONCLUSIONS

We have presented a pure photogrammetric strategy for georeferencing of sequence of images captured by MMS during the periods of GPS signal outages which frequently occurs during navigation in downtown areas. The accuracy of the procedure based on the RMSE analysis between the reconstructed trajectory and the simulated one, turned out to be compatible with the accuracy of the MMS in normal operating conditions for GPS signal outages up to 500m.

The importance of having a good estimate for the interior orientation parameters, as a camera calibration output, was not addressed for this particular application. However, it goes without saying that the results critically depend upon the camera calibration. Moreover, the boresight calibration of the cameras is also required with high accuracy. Future work will include testing the proposed technique using real data sets collected using the VISAT Van.

7. ACKNOWLEDGEMENTS

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