

COMMON ADJUSTMENT OF LAND-BASED AND AIRBORNE MOBILE MAPPING SYSTEM DATA

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ABSTRACT:

Presently, numerous types of geospatial data have become available for both industrial and research use. These types of data are collected by different sensors and from different platforms. Therefore, they are substantially different in physical nature, amount/type of information, and geometric/radiometric resolutions. Multi-sensor data fusion techniques combine data from multiple sensors and related information from associated databases, to achieve improved accuracies and more specific inferences than could be achieved from a single sensor. Many researchers have proposed different fusion schemes for integrating different sensory data. Yet, there is less amount of attention towards the fusion of airborne (AMMS) and land-based (LMMS) mobile mapping systems imagery/navigation data. Although, this integration scheme may be thought to be simple or similar to other optical-to-optical registration process, its practical implementation carries many challenges. Images captured by (LMMS) and (AMMS) are different in the sense of direction, scale, coverage, hidden/visible features. Consequently, the integration between the data captured by AMMS and LMMS is of high potential since both image/navigation data sets are complementary and can be integrated to complete the picture about the earth's surface. This paper proposes a fusion scheme for the overall objective of improving the 3D mapping accuracy. This fusion scheme aims at creating a unique model, which can be visualized in several contexts of application. Also, the common adjustment of terrestrial and aerial photogrammetric networks recovers/enhances sensors georeferencing information—a way for LMMS bridging during GPS outages or georeferencing aerial images block. The proposed integration framework uses different matching entities of lines (e.g. road edges and lane lines) in addition to the traditionally-used point-based approach. Mathematical model of collinearity condition has been adapted to suite multi-camera system. In this paper, we consider the scientific and the technical issues about the strategy of the proposed fusion scheme. The used modalities will be coming from the simulated VISAT LMMS platform and other sources.

1. INTRODUCTION

The number of sensors, orbiting our globe, is growing steadily over the years. Data, collected by such sensors and from different platforms, are considerably different in physical nature, amount/type of information, and geometric/radiometric resolutions. It is firmly confirmed through plethora of researches that no single sensory data can provide the optimal solution for a specific query. Consequently, data fusion/integration is considered for a better solution/information recovery about the object being captured. The topic of multi-sensor data fusion has received a lot of attention over the years by the scientific community for military and non-military applications. Many researchers have proposed different fusion schemes for integrating different sensory data. However, there is less amount of attention towards the fusion of imagery/navigation data of airborne and land-based mobile mapping systems.

Mobile Mapping Systems (MMS) can be classified according to the physical carrier into land (LMMS), and airborne (AMMS) based systems. Images captured by (LMMS) and (AMMS) are different in the sense of direction, scale, coverage, hidden/visible features. Consequently, the integration between

the data captured by the two systems is of high potential hence both image/navigation data sets are complementary and can be integrated to complete the picture about the earth's surface.

In this paper, we introduce a novel scheme for the fusion AMMS and LMMS data through adapting many of the existing tools to fit the special requirements of such fusion scenario. The investigation and the drawn conclusions are based on simulating modalities from the VISAT platform and other sources. This research aims at creating a unique model, e.g. facets-based, which can be visualized in several contexts of application and serves different scientific communities. In section 2, the general benefits of the data fusion are listed, and some examples are illustrated. Section 3 is devoted to discuss the potential for the proposed fusion scheme. Both sections 4 and 5 describe the math models for matching entities after applying the necessary adaptations to fit the proposed fusion scheme. Section 6, draw the main special requirements and features of the fusion scheme framework. The preformed simulations are described in section 7 as well as the obtained results. Conclusions are drawn in section 8.

2. BACKGROUND

The last fifty years have witnessed a rapid evolution of the data used in Geomatics applications. This evolution was inspired by the development of (a) fast digital computers, (b) new high resolution satellites, (c) the development of integrated, navigation sensors/systems, and (d) general technological advancements. As a result, numerous types of sensory data have become available and are classified according to:

- 1- Color information (e.g. color and pan images).
- 2- Spectral bands (multi/hyper spectral).
- 3- Recording media (analogue and digital).
- 4- Sensor Dimensionality (frame, line, and panoramic).
- 5- Platform/sensor location (satellite, aerial, terrestrial).
- 6- Physical nature of the collected data (optical, Non-optical data like LiDAR (Light Detection And Ranging)).

The topic of multi-sensor data fusion has received over the years a lot of attention by various parties, see for example Hall and Llinas, 1997. As noted by (Hong, 1999), these techniques have the overall objectives of achieving numerous benefits, such as:

- Robust operational performance
- Extended spatial/temporal coverage
- Reduced ambiguity
- Increased confidence
- Improved detection performance
- Enhanced resolution (spatial/temporal)
- Increased dimensionality

Many researchers have proposed different fusion schemes for integrating different sensory data. This fusion process can be broadly classified into optical-to-optical, optical-to-nonoptical, and nonoptical-to-nonoptical.

To name few works on data fusion, Lee et al., 2002, presented a study on performing aerial triangulation using frame, push broom, and whisker broom cameras thus applying the concept of multi-sensor aerial triangulation (MSAT). Lee and Choi, 2004, merged the terrestrial images and terrestrial lidar cloud points to reconstruct 3D GIS building models with more realistic geometric and radiometric properties. Iavaronea and Vagnersb, 2004, generated complete and accurate solid model for Toronto city hall in Toronto by combining aerial and tripod-mounted LiDAR data. In fusion literature, there is almost no attempt towards the fusion of airborne and land-based mobile mapping systems imagery/navigation data.

3. POTENTIAL OF THE MMS DATA FUSION

Mobile mapping concept has yielded to a breakthrough to the Geomatics applications and opened new avenues for both research and industry visions. Mobile mapping systems (MMS) can be installed on different platforms. Regardless the platform, MMS operate by attaching the navigation sensor to mapping sensors in a rigid connection. The navigation sensors provide sufficient information for estimating the position and the orientation of the mapping sensor with respect to the world coordinate frame (El-Sheimy, 1996). While, mapping sensors are used to locate object features with respect to their local coordinate system. By combining the navigation and mapping sensor data, the mapping process can be done in an efficient, economic manner and almost everywhere. The mapping sensors

may include, but not limited to, frame/line/panoramic digital camera(s), laser scanners, and different Radar sensors. Thus, MMS can, in principle, provide multiple mapping data sources collected at the same time.

As stated earlier that images captured by (LMMS) and (AMMS) are different in the sense of direction, scale, coverage, hidden/visible features. In LMMS, the direction of the camera axis is almost horizontal. While in AMMS, the camera optical axis is usually looking down. Additionally, in LMMS the features of interest are usually traced in images captured at 20-50m away from the camera while, in AMMS the camera-object distance ranges from 300m to few several kilometres above the earth's surface. Therefore, one aerial image may cover the operational range of several hundreds of LMMS image sets. In AMMS, the images are earth-top views which contain mainly building roofs and road planes. LMMS' images are complementary to AMMS' images as they include the building sides and more road details.

With data fusion of images captured by different kinds of sensors (multi-modality), 2D images coming from the same vehicle, aerial images, an important issue will be the correct geo-referencing of data, which means a good localization (position, orientation) in a common terrestrial frame before model creation.

Based on the above discussion, the integration between the data captured by AMMS and LMMS is of high potential hence both image/navigation data sets are complementary and can be integrated to complete the picture about the earth's surface. As a photogrammetric rule of thumb, the mapping accuracy is relatively worth in the direction of the camera axis due to intersection geometry. Hence, the camera axis in the LMMS and AMMS are almost perpendicular. A combined solution, from both systems observations improves the 3D quality of the object space model. In (Hassan et al., 2006b), a photogrammetric strategy for bridging LMMS during GPS signal outage spans has been introduced. The framework has been developed based on photogrammetric reconstruction using LMMS and point features only. The new proposed integration framework, of both data sets with different matching entities (i.e. lines and points), can make the reconstruction of the LMMS trajectory easier and more practical. Finally, as a major potential of this frame work, if the aerial images involved have no or poor georeference information—as huge image data base still exists—the georeference information can be recovered efficiently. The georeference of the aerial images, in this case, will be mainly based on the 3D control line extracted from LMMS (Cheng et al., 2007).

The proposed three applications for the investigated fusion scenario serve different community. Enhancing the 3D object space accuracy is a pure mapping application. Additionally, aiding land-based systems in urban blocks is one of the navigation community's concerns. Finally, georeferencing airborne images using the proposed fusion scheme presents a fast and efficient solution for many photogrammetric applications.

4. MATHEMATICAL MODEL

Traditional designs of photogrammetric adjustment frameworks have been implemented based on indirect orientation concept,

where camera position and orientation are estimated based on the similarity transformation function between the 3D coordinates of the ground control point and their respective 2D image measurements.

The trend in designing photogrammetric adjustment has changed significantly, with the availability of navigation sensors together with mapping sensors (i.e. mobile mapping systems), thus applying the concept of **Integrated Sensor Orientation (ISO)**. The design of the bundle adjustment framework has been extended to include all the available information about the block configuration like platform position/attitude, as observed by GPS/INS integrated systems. Additionally, camera characteristics, as camera calibration procedure output, can be also included, (Ebner, 1976). All the introduced information is involved with appropriate weighting schemes.

Most of the scientific/educational, see for example BLUH, (Linder, 2003) or commercial photogrammetric frameworks, see for example (HJW), (INPHO's), and (NOOBEED)¹, are mainly designed for aerial applications, with one possible camera attached, with possible integration of navigation information as observed parameters. However, this treatment makes it only suitable for single camera system per exposure station (i.e. AMMS).

In case of integrating data from both LMMS and AMMS, a photogrammetric framework, Figure 1, specially designed for mobile mapping systems, is required. This framework is different from other frameworks for photogrammetric operations. This difference is more pronounced, if the system hardware includes more than one camera, fixed to the navigation sensor.

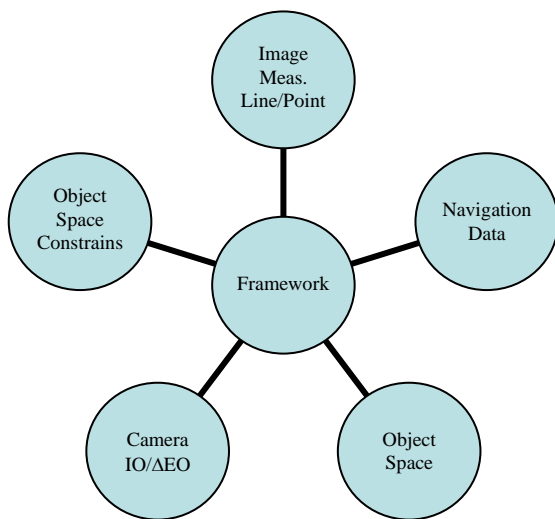


Figure 1: Framework Input Data

Usually AMMS are designed to have one camera, while LMMS always have multi-camera to increase the field of view of the

¹ HJW, Geospatial <http://www.hjw.com/index.htm>
 INPHO's, Photogrammetric System.
http://www.inpho.de/index.php?seite=index_en&navigation=1896&root=165&kanal=html
 NOOBEED <http://noobeed.com/index.htm>

system (e.g. the VISAT imaging system configuration, has 8 cameras with 330° panoramic field of view). In this case, a change of the definition of the exposure station has to take place. For a single camera system, the physical exposure station is the location of the camera perspective center at the images exposure time. In case of multi-camera system, the exposure station is no longer related to the camera perspective center rather than the navigation sensor center (i.e. IMU triad center), see Figure 2. The different camera perspective centers are connected to the exposure station through a linear offset and series of rotations. The photogrammetric adjustment framework, based on multi-camera concept, models the system more efficiently and provides the ability to perform the system calibration—an extremely important task in mobile mapping system cycle.

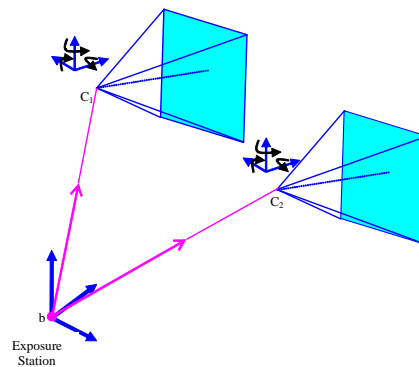


Figure 2: Multi Camera System

A more general form of collinearity model for frame cameras is given:

$$\begin{pmatrix} x_{ijk}^r \\ y_{ijk}^r \\ f^{(j)} \end{pmatrix} = 1/\lambda_i \cdot R_b^{c(j)} \left[R_m^{b(k)} \cdot \begin{pmatrix} X_i - X^{e(k)} \\ Y_i - Y^{e(k)} \\ Z_i - Z^{e(k)} \end{pmatrix} - \begin{pmatrix} \Delta X^{(j)} \\ \Delta Y^{(j)} \\ \Delta Z^{(j)} \end{pmatrix} \right] \quad (1)$$

Where:

$x_{ijk}^r, y_{ijk}^r, f^{(j)}$	Refined image measurements of point (i) in an image taken by camera (j) at the exposure station (k)
$R_m^{b(k)}$	The system attitude rotation matrix at the exposure station (k)
$R_b^{c(j)}$	Camera delta rotation matrix as a function of boresight angles
$X^{e(k)}, Y^{e(k)}, Z^{e(k)}$	System position, which are equivalent to the exposure station in multi-camera framework
$\Delta X^{(j)}, \Delta Y^{(j)}, \Delta Z^{(j)}$	Lever arm component
X_i, Y_i, Z_i	Ground coordinate of point (i)
λ_i	Unknown scale factor

5. MATCHING ENTITIES

Until late eighties of the previous century, photogrammetric measurements were still based on point-wise measuring procedure. Point-wise approach requires that measured image points in one image have to be identified on another image(s). These point measurements must be conjugate and corresponds to exactly the same 3D object point. The mathematical formula for expressing image to object correspondence is based on collinearity equation. The other approach of introducing higher order primitives, usually referred as feature based assumes that the measured points belong to certain object feature, which fulfils a certain path in 3D space. The attractiveness of applying feature based approach is that point to point correspondence is no longer required. Control linear features can be used in all photogrammetric procedures, in single image resection and triangulation. The use of linear features is applicable in mapping of either: man-made areas where plenty of buildings, and road edges; or natural areas where river bank lines, coast lines and vegetation boarders can be involved as linear features (Heikkinen, 1992). Image space linear features are easier to extract than point features. Meanwhile, object space linear features can be directly derived form LMMS, GIS databases, and/or existing maps, (Habib and Morgan, 2003).

Yet, the inclusion of linear features provide more constrained solution for the exterior orientation parameters, and better distortion modelling, however in some applications, is an option like for example camera calibration. Meanwhile, the inclusion of linear features becomes necessity, when they become the only possible (realistic) similarity entities for example in case of integrating LiDAR and photogrammetric data (Habib et al., 2004b). Another example that demonstrates the importance of involving linear feature constraints in photogrammetric triangulation is the multi-sensor triangulation, where various sensory data with different geometric resolution are involved. In this case, the measurements of conjugate linear features constitute a great advantage, for their ease identification in different resolution images due to their high contrast (Habib et al., 2004a). The linear feature constraint, see Figure 3, is expressed mathematically as follows:

$$(\vec{V}_1 \otimes \vec{V}_2) \bullet \vec{V}_3 = 0 \tag{2}$$

Similar to point features, linear features can be classified into tie and control lines. Linear features, extracted from LiDAR data, are control lines and can be used in different photogrammetric operations. Linear features are useful to relative orientation only when the same line is observed in an image triplet (at least three images). In this case, the produced planes will intersect in the object line indicating the quality of fit.

The framework, introduced in this paper, involves linear feature constrain since LMMS, with multi camera system, are usually operated over road networks, where plenty of straight road edges and lane line markings are available. The same features will be mostly visible in AMMS images. Additionally, some object space realistic constrains can be applied on linear features like horizontal/vertical lines, and parallelism of object lines. Downtown blocks have plenty of these constrains like building edges and lane line markings. These constraints help in the estimation of some of the georeferencing parameters. Thus,

linear features present major matching entities in the proposed framework.

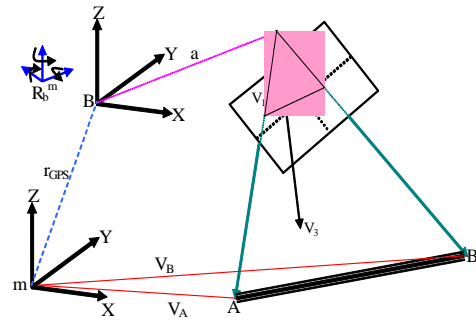


Figure 3: Linear Feature Constrain

The implementation of the linear feature constraint can be implemented in a number of ways. The two vectors V1 and V2 (in Figure 3) can be either replaced by their corresponding object space vector that joins the perspective centre and the end/start point. Alternatively, they can be replaced by their corresponding image space vector after back projecting the line end points to the image space. Image space approach is much efficient than the object space as it provides much higher convergence rate than the object space cost function. This may be attributed to the consistency of the system of equations with those equations coming from collinearity constrain.

6. FRAMEWORK

The proposed framework for performing such integration scenario is considered as a generic bundle adjustment that can be easily extended to include additional matching entities and also to add any functionality if necessary. In order to make the developed framework fits the integration between mobile mapping data, many features have to be added.

One of the basic modification, being a multi-camera enabled, which is a must when involving land based data. This can be done by involving another rotation matrix as a function of boresight angles. Of course, any order of rotation is possible. Regardless of the order, the three rotation angles are included as parameters in the adjustment. A disadvantage of this procedure is that the addition of these angles necessitates rather fundamental changes to the implementation of the adjustment, as the collinearity equations become functions of six angles instead of just three. This, in turn, makes the linearization of the collinearity equations considerably more complex. However, the necessity of changing the adjustment model presents a good opportunity to re-parameterise the R_M^C (rotation matrix between camera and mapping frame) rotation matrix in terms of the roll, pitch, and azimuth angles. This enables the values observed INS angles as well as their covariance to be included in the adjustment.

Additionally, as compared to other optical-to-optical multi resolution fusion, the proposed frame work involves linear feature measurements implementation for reasons mentioned in section 5. Another reason for using linear feature which is tightly related to the land based mobile mapping system bridging is that using linear feature has the advantage of

working in extreme cases where occlusions exist. These occlusion problems are always exhibited during navigation in downtown area as resulted from parking or heavy traffic. Finally, with linear feature, the reconstruction process is practical one as compared to strategies that rely on point feature only.

Of similar importance to the previous features, the proposed framework is designed to be flexible when it comes to the treatment of the different adjustment objects in the adjustment. Two examples are given herein. Firstly, different scientific communities use certain parameterization for the rotation matrix: navigation community usually expresses the body attitude in space using roll, pitch, and azimuth; while the photogrammetric community use sequence of Euler rotations. Therefore, the framework must allow the parameterization of each exposure station independently using any parameterization set. Secondly, when dealing with camera interior orientation (IO), distortions in small format cameras can be modelled using first or second order polynomial. Meanwhile, when dealing with large format cameras (aerial), distortion models are more complicated and need higher order polynomial. Design flexibility allows attaching different distortion models to different cameras independently.

7. SIMULATIONS AND RESULTS

In order to prove the applicability of the proposed fusion scheme, several simulations have been performed. The first simulation (S1) tests the possibility of using LMMS navigation and pictorial data to georeference airborne images based on point measurements. The photogrammetric network consists of four aerial images (A-1 to A-4), and 8 LMMS images taken from 4 land exposure stations, with 4 common ground points T1 to T4. The aerial images are taken with RC30 cameras at 1000m above ground level, see Figure 4. A minimum of three common points are required for datum definition. Other tie points between aerial images are still required.

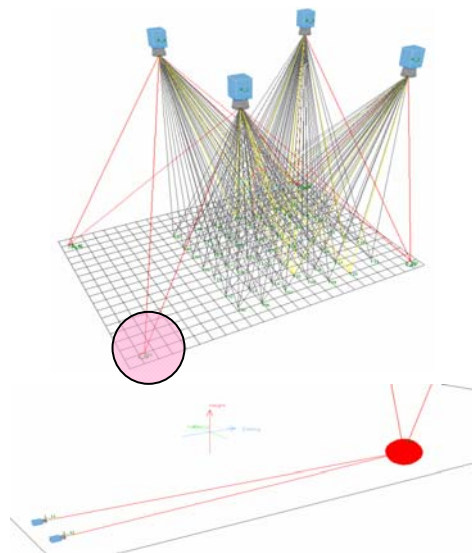


Figure 4: Photogrammetric Network Configuration

Table 1 shows statistics of the true errors as estimated from the simulated trajectory and their corresponding estimated value for airborne positions and attitude; while Table 2 displays the

standard deviation results. Comparing the results of the true errors and the estimated standard deviation, one can reveal that the results of the accuracy estimate are pessimistic.

	Max.	Min.	Mean
E (m)	0.123	0.012	0.084
N (m)	0.137	0.011	0.056
H (m)	0.042	0.002	0.023
W (")	20.3	1.1	6.8
P (")	11.5	6.1	9.0
K (")	8.8	3.2	5.9

Table 1: Actual Absolute Errors Statistics for Point Based Scenario

	A-1	A-2	A-3	A-4
E (m)	0.088	0.110	0.100	0.090
N (m)	0.110	0.130	0.130	0.110
H (m)	0.055	0.074	0.077	0.056
W (")	19.8	25.2	25.2	20.2
P (")	14.0	19.4	18.4	14.4
K (")	6.5	7.2	7.6	6.5

Table 2: Adjustment STDEV

Previous simulation, using point feature, implements one step adjustment for both LMMS and aerial images measurements. The application of the previous simulation is limited the visibility of point feature in aerial images. To ensure such condition, point feature need to be signalized before taking the aerial images. This constrain is not realistic, time consuming, and sometimes impossible when used with old aerial images databases. Moreover, occlusions from moving and parked cars may prevent the measuring process. Considering the limitation of the previous scenario, another simulation (S2) based on line measurements has been performed. The simulation uses the same photogrammetric network configuration as in S1. A major advantage of this scenario is that conjugate points measurements, between the two data sets, are no longer required. The linear matching entities simulated from lane line marking which present the best alternative due to their ease measurement due to high contrast. Table 3 summarizes the statistics of the true errors for the aerial images (A-1 to A-4).

	Max.	Min.	Mean
E (m)	0.067	0.026	0.045
N (m)	0.055	0.010	0.030
H (m)	0.069	0.003	0.034
W (")	8.8	0.5	5.3
P (")	12.6	0.1	8.7
K (")	16.3	5.7	10.5

Table 3: Actual Absolute Errors Statistics for Line Based Scenario

The selected common lines between the two data sets have to be skewed lines. It is obvious from the obtained results that the

two alternatives provides similar results however, line-based scenario is more practical.

Another simulation (S3) has been tested to check the object space accuracy if the navigation solution of the two data sets is good. Using the same photogrammetric configuration in S1, the image measurements are generated with appropriate noise level. The land data is then processed alone. Another result is obtained using both datasets. Table 4 presents the results in both cases and holds a comparison to present the percentage of improvement for the four common ground points T1 to T4.

Po.	LMMS Only		AMMS & LMMS		Improvement		
	2D	3D	2D	3D	2D	H	3D
T1	0.130	0.131	0.014	0.016	9.0	0.9	7.9
T2	0.163	0.164	0.037	0.037	4.4	0.5	4.4
T3	0.128	0.129	0.019	0.021	6.8	0.8	6.1
T4	0.034	0.037	0.016	0.019	2.1	0.9	1.9
Ave.					5.6	0.8	5.1

Table 4: Object Space Accuracy Enhancement

Planimetric accuracy (Horizontal) is improved by the fusion algorithm with average of 5.6 times while the vertical accuracy deteriorates (compared to LMMS alone). This is not acceptable in terms of filtering and adjustment theories. This might be interpreted as a result of non proper weighting scheme or due to small number of points used to confirm the conclusion. In general the 3D accuracy of the common points is improved by 5 times factor. The results of this simulation increase of LMMS operational range by fusion with high resolution airborne images, which has been limited by weak intersection geometry.

The last performed simulation (S4) is used to support the innovative idea of using airborne images to improve/estimate the georeferencing of the land based systems when they exhibit large drifts due to GPS signal outages. A 500m trajectory was simulated. Two aerial images are simulated with two lines (two blue lines shown in Figure 5) in common with the land-based image set. These two lines simulating the lane line marking of the lane in which the LMMS van is moving. The linear features are back projected to the image space to generate line image measurements based on a true trajectory. Then, the navigation solution is contaminated with large biases (up to 20m) in position and several degrees in attitude. The data is then processed using the developed framework. The adjusted trajectory is compared to the true one.

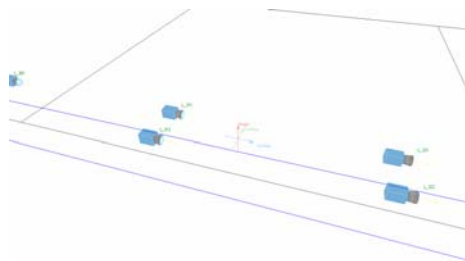


Figure 5: LMMS Bridging Simulation

The results show that the van heading can be perfectly reconstructed. Both roll and pitch angles can be recovered with accuracy of 1°. The vertical direction accuracy is less than 1 cm and similar results were obtained for the direction perpendicular to the van trajectory. However, the state in the direction of van movement direction is not observable. In other words, moving the van in the forward direction will not affect the quality of fit and therefore the corresponding parameter will not be updated. This can be solved by having other lines which is not perfectly parallel to the van trajectory or having additional fewer point measurement either between the successive LMMS image set or connected with the airborne images if possible.

8. CONCLUSIONS

The results presented in this paper reflects an ongoing research for establishing framework for integrating land-based and airborne mobile mapping system data—an integration scheme that received less attention in mapping, navigation, or photogrammetric literature. Both data sets are complementary in terms of information, resolution, and geometry. The developed framework adapts many of the existing tools to be generic enough to perform the proposed integration scheme. In this paper, we propose three vital applications for the fusion process. Firstly, land-based mobile mapping system (e.g. VISAT) can provide fast and efficient control points/lines for georeferencing airborne image sets. The presented georeferencing strategy focuses on using linear features due to their extreme advantages for real life applications. Secondly, the proposed integration scheme enhances the 3D object space accuracy. Adding airborne to land-based data in one adjustment session reinforced the weak geometry in the imaging direction. This advantage potentially increases the operational range of land-based mobile mapping systems (usually was limited to 30-50ms).

Thirdly, the framework proposes a practical strategy for improving land-based mobile mapping navigation accuracy in urban areas by fusion with airborne images. We focus on using the available linear feature like lane lines and road edges as matching entities. The obtained results are promising. More testing is needed to draw the guidelines for performing such strategy for bridging LMMS by fusion with airborne data.

Our future works include the application object space constrains. Also, the earth fixed frame implementation will be tested for georeferencing image sets which cover large areas. Optimal weighting strategy is included in our future plan. Once all the features of the proposed framework are implemented, the developed framework will be tested using real data.

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