Directly Georeferencing Terrestrial Imagery using MEMS-based INS/GNSS Integrated Systems

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SUMMARY

Simultaneous developments in Global Navigation Satellite Systems (GNSS) and Inertial Navigation Systems (INS) have lead to integrated INS/GNSS systems that can provide direct-georeferencing for image-based mapping systems. Such systems directly provide the position and attitude of the camera, necessary for subsequent mapping from the imagery, rather than it indirectly being determined from object-space control points as was traditionally done. This has lead to improvements in both the efficiency and cost-effectiveness of spatial data collection. The current implementation of the navigation sensors are based on high priced, restricted handling, navigation or tactical grade IMU. These constrains limits the use of Mobile Mapping Systems (MMS) in developing countries. Low cost inertial sensors known as MEMS offer a cheap and flexible tool for direct georeferencing.

In this paper, the possibility of using MEMS-based INS/GNSS systems for directly georeferencing terrestrial imagery is investigated by using backward smoothing to improve the integrated system accuracy. Field test datasets collected by land vehicles under intermediate GNSS blockage environments were processed by the proposed algorithm. Results have shown that backward smoothing can significantly improve the direct-georeferencing accuracy when compared to conventional forward Kalman filtering, especially the position accuracy during GNSS signal outages. The concept of dynamic system calibration, suitable for calibrating the MMS based on MEMS INS/GNSS integration, is presented. The achieved accuracy is promising for the direct georeferencing of some close-range portable/vehicular photogrammetry systems which require lower levels of georeference. The MEMS-based mobile mapping system has unique advantages of low-cost, small size, and no government regulation.

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1 INTRODUCTION

The first formal definition of the term "mobile mapping" was offered in 1995 by Dr. John Bossler, director of the Center of Mapping at The Ohio State University: "Mobile mapping is a technique used to gather geographical information, such as natural landmarks and the location of roads, from a moving vehicle. The technology has been around for decades, but recent advances in computers and satellites have made mobile mapping easier, cheaper and more accurate". The demand for highway infrastructure information represented the initial driving force behind the development of mobile mapping platforms (Li and Chapman, 2005). All MMS share the concept of integrating a set of sensors mounted on a common platform and synchronized to a common time base. Such systems are usually operated in kinematic mode. In principle, they are capable of operating and collecting navigation and imaging data that are sufficient to do the mapping process without the need to establish costly, and time consuming terrestrial ground control networks. They provide high level of flexibility as such systems can be immediately deployed everywhere on the globe without the need for identifying existing ground control (e.g. Mostafa and Schwarz, 2000, Hutton et al, 1997).
Unfortunately, the INS/GNSS systems used for direct georeferencing of the MMS have near-universally used navigation-grade or tactical-grade Inertial Measuring Units (IMUs). The high cost of such IMUs ($15,000-$100,000), their considerable size and their restricted handling regulations have limited their use, particularly in developing countries. Recently, new types of INS/GNSS systems have been developed that use low-cost inertial sensors based on Micro-Electro-Mechanical Systems (MEMS) technology. They are chip-based sensors that are small in size (micrometers to millimeters), lightweight (milligrams), extremely inexpensive ($5-$30), and consume very little power (microwatts). Unfortunately, due to their fabrication process MEMS inertial sensors have large bias instabilities and high noise. Hence, when they are integrated with GNSS, the resulting systems provide poor navigation accuracy when the GNSS signals are blocked for even short periods of time. Thus, special considerations have to be taken into account for MEMS INS/GNSS integration to meet the requirement for georeference of the MMS.

In this paper the concept mobile mapping is briefly introduced. MMS based on MEMS INS/GNSS integration are then discussed. The developed MEMS navigation system is introduced and the field test results of different MEMS data processing strategies are illustrated. Dynamic system calibration are introduced and tested. The mapping accuracy of such system is analyzed and finally conclusions are drawn.

2 MOBILE MAPPING

Virtually all MMS systems include, but are not limited to, a GNSS receiver, an inertial measurement unit (IMU), and CCD cameras. Some systems also include additional navigation aids like distance measurements units (DMI) or digital compasses. The mapping sensors can be extended to include 3-D laser scanners, IFSAR, and ground penetrating RADAR. The navigation data streams arising from the GNSS and IMU sensors are first processed by a Kalman filter that combines the information in an optimal way. The output of this processing step is a trajectory description file, including the position and attitude of the IMU, with frequency at the IMU output frequency or less; usually, better than 100Hz. Based on event mark pulses of the camera the captured images are time-tagged. The position and attitudes of each camera are then determined using the navigation trajectory, the time tags, and the inter-sensor calibration parameters. The mapping process becomes a straightforward step by doing space intersection of the conjugate light rays to obtain the 3-D object space coordinate of the point under consideration. Symbols can be attached to the captured point features to describe their attributes. This symbol assignment process facilitates the integration with GIS software databases.

2.1 Direct Georeferencing

The formulation of the direct geo-referencing formula is rather straightforward. Equation 1 is the basic mathematical model for the mapping process for mobile mapping systems either being aerial or land-based (Hassan et al., 2006):

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

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/GNSS) 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 IMU 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

It should be emphasized here that the accuracy of the mapping depends on three main elements: the navigation solution accuracy, the inter-sensor calibration, and the imaging configuration. The core of this paper is to investigate the impact of different MEMS-based INS/GNSS navigation data processing strategies as well as the system calibration procedures.

2.2 VISAT: A Next Generation MMS

The motivation for this research arose during the development of VISAT MMS. VISAT (Video, Inertial, and SATellite GPS), developed in the University of Calgary in the early 1990s, was one of the first terrestrial MMS. Recently, an improved version – shown in Figure 1 – was developed (AMS Inc., 2006). The system's data acquisition components include a strapdown INS system, a dual frequency GPS receiver, 8 colour digital cameras, and an integrated DMI hookup on the speed sensor of the vehicle, and the VISAT™ system controller. The function of each component can be subdivided into primary and secondary tasks. In terms of primary functions, the camera cluster provides up to 330-degree field of view with respect to the VISAT™ reference, which in most cases is the perspective center of one of the cameras. The DMI provides the van traveling distance to triggers the cameras at constant intervals. The data-logging program, VISAT™ Log, allows for different camera configurations and different image recording distances or trigger the camera by time if necessary (both can be changed in real-time). In terms of secondary functions, the camera cluster provides redundancy, i.e. more than two images of the same object. The DMI data can be used to update the INS data if the GPS signal is blocked for periods longer than the INS bridging level required to fix the GPS integer ambiguities. Using VISAT™, mapping accuracies of 0.1 - 0.3 m for object distance of 50m from the van can be achieved in urban or highway environments while operating at speeds of up to 110 km per hour.

Figure 1 VISAT™ Van 2006

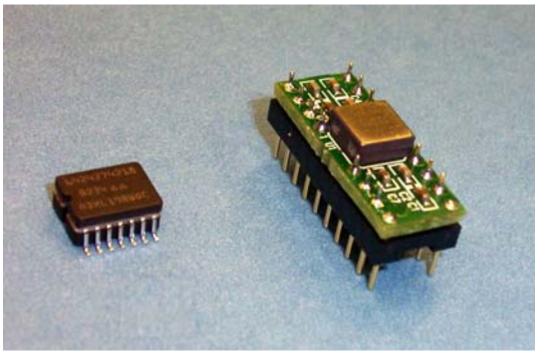
Unfortunately, by incorporating a high-grade IMU, the use of VISAT is limited to countries and organizations that can both afford the technology and that are allowed to operate the IMU. These are relatively restrictive conditions, and consequently there is interest in the development of alternative mobile mapping systems that use MEMS based IMUs.

3 MEMS-BASED INERTIAL NAVIGATION SYSTEMS

3.1 Inertial Navigation and MEMS

Integrated INS/GNSS systems provide an enhanced navigation system that has superior performance in comparison with either stand-alone system as it can overcome each of their limitations. The complementary nature of inertial and GNSS based navigation systems can be used advantageously in navigation system design. Unfortunately, high costs and government regulations are preventing the wider adoption of high quality IMUs.

MEMS technology enables inertial sensors on a chip. In addition to being compact and portable, MEMS-based IMUs cost much less than the high-quality IMUs traditionally used in inertial navigation systems. However, current MEMS suffer from noisy measurements and poor stability. Therefore, such devices are not usable by themselves as a navigation system. They have to be integrated with a complementary system such as GNSS to maintain acceptable navigation accuracy. Additional effort to adapt the navigation algorithm to MEMS' poor performance is necessary as well.
The Mobile Multi-Sensor Systems (MMSS) research group at the University of Calgary developed a MEMS-based navigation system in 2005. The IMU was built using the most popular low-end MEMS inertial sensors in the market: ADXRS150E (ADI 2003a, 2003b) and ADXL105AQ (ADI 1999) from Analog Devices Inc. (ADI), shown in Figure 2.


a) MEMS sensors from ADI

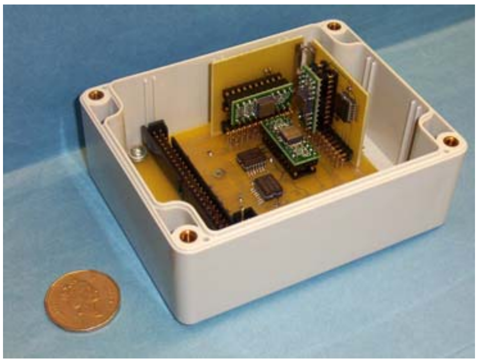

b) MEMS IMU

Figure 2 Photos of MEMS inertial sensors and IMU

3.2 Navigation Algorithm

To derive the navigation information from the signals of the developed MEMS-based INS/GNSS system, the MMSS research group developed AINS™, an Aided Inertial Navigation System MATLAB® Toolbox for integrating GNSS and INS data (Shin and El-Sheimy 2004; Shin and El-Sheimy 2005). AINS™ uses an extended Kalman Filter (EKF) to optimally combine GNSS positions and velocities with inertial data. Data from other aiding sensors, such as odometers or heading sensors can also be used, or non-holonomic constraints can be applied. In addition to forward filtering, the toolbox can perform backward smoothing using the Rauch-Tung-Striebel (RTS) smoother. The smoothing solution can be basically regarded as the optimal weighted average of the forward filter and backward filter. It essentially makes full use of the information of the whole dataset to estimate the position and attitude at each time epoch. Therefore its accuracy is normally significantly better than the forward Kalman filtering. Smoothing is very appropriate for post-processing missions, including mobile mapping.

3.3 Test Results using Various Processing Strategies

The MEMS-based navigation system was tested in a set of land-vehicle field tests. Figure 3 shows the trajectory of a typical field test in an urban area with relatively good GPS signal availability. Double-difference carrier phase derived GPS positions and velocities were used as the GNSS update, because they are available for post processing in the mobile mapping system without much additional cost.

To investigate the accuracy and error behavior of the MEMS system, a navigation grade IMU, the CIMU from Honeywell (0.005 deg/h bias drift), was included in the test to generate a reference trajectory. The optimal solution of GPS/CIMU (smoothing) was used as the true values (position and attitude) for MEMS system. This “true” solution will also be used for the mapping simulation in the next section.

In this section, navigation results of the MEMS system will be presented and analyzed. Results based on different processing strategies will be compared:

- Forward filtering
- Backward smoothing
- Backward smoothing with non-holonomic constraint.

The effect of the vehicle dynamics and GPS signal quality to the navigation results (position and attitude) will be discussed. At the end of this section, the best possible performance of the MEMS-based navigation system will be summarized.

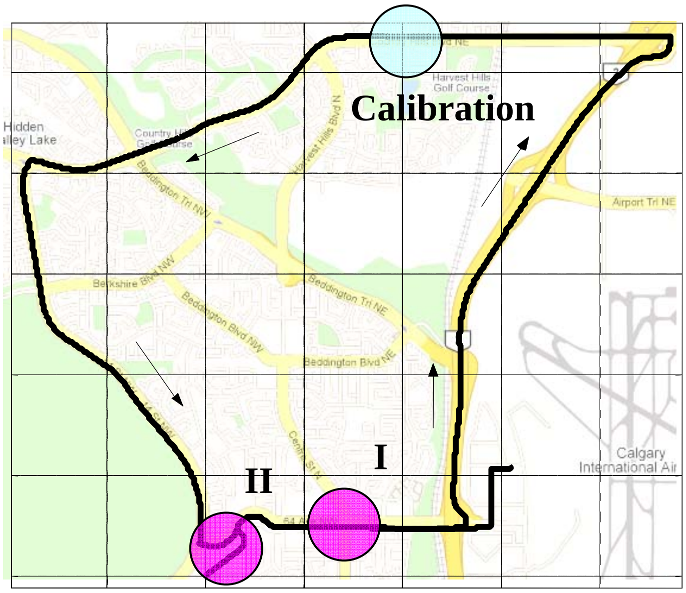


Figure 3 Trajectory of the field test

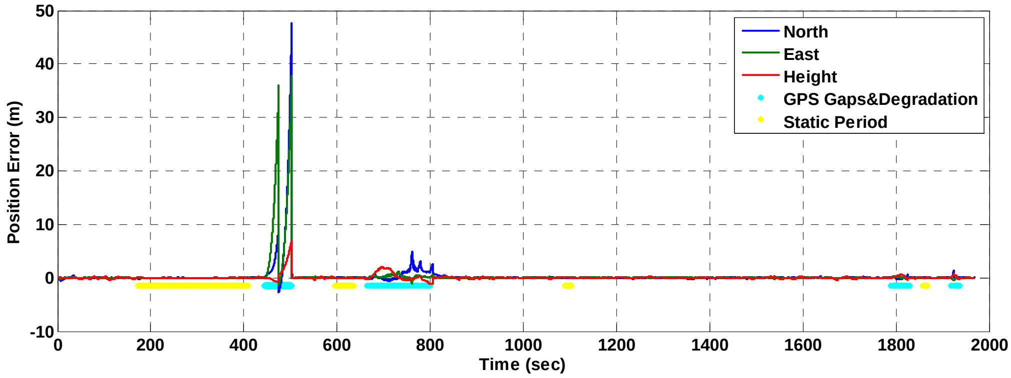
3.3.1 Forward filtering

MEMS IMU data was first processed by the forward filter (EKF). Figure 4 shows the errors of the navigation results. Here the cyan color highlights the time periods that GPS signal was blocked or degraded, while the yellow color highlights the time periods where the vehicle was stationary. In Figure 4a, it can be seen that when GPS signal was under normal condition the position error was small, with an RMS of about 0.1m. When there was GPS signal outage or degradation, however, position error increases dramatically. For example, the two adjacent 30s outages between 443s and 503s caused position drift of almost 50m, and the GPS signal degradation between 665s and 804s generated 5m position error.

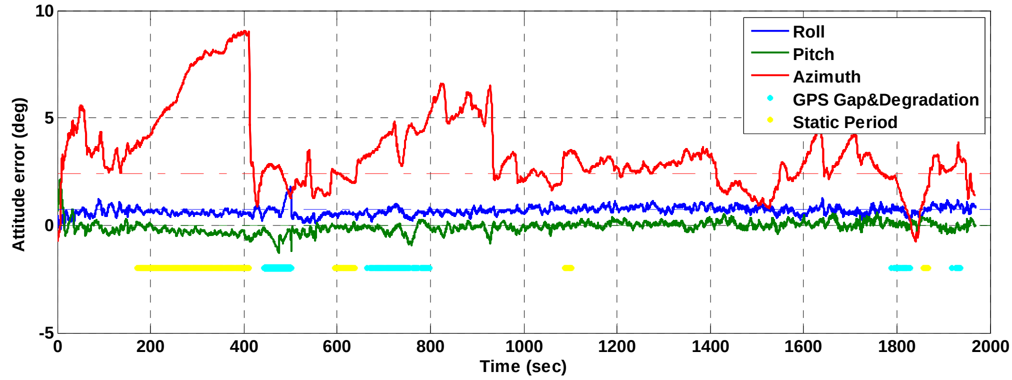
In Figure 4b, the roll and pitch angles are accurate and stable, but the azimuth was in error by as much as 6.5 deg. Detailed investigation has shown that the azimuth error is strongly related to the vehicle dynamics. When there is little dynamics, the observability of the azimuth by the GPS update is almost zero, causing the azimuth to diverge (Niu and El-Sheimy 2005). A typical example is the 4 minute stationary period from 172s to 410s (zero kinematics). The azimuth drifted to 6.5 deg until the vehicle started moving again. Therefore, it is recommended to intentionally make some maneuvers (speed up/down, turns, etc.) regularly to keep the accuracy of the MEMS systems during the mobile mapping survey.

Here please note there are some biases in the attitude errors, i.e. +0.75 deg for roll, 0.0 deg for pitch, and +2.4 deg for azimuth. These biases come from the mounting misalignment between the MEMS IMU and the reference system (CIMU). They are physically existed and do not belong to the estimation error. Later it will appear in the boresight calibration of the camera in the next section.

The results shown in Figure 4 are typical for MEMS navigation systems. Obviously they are far from the requirements of mobile mapping. The navigation performance has to be improved significantly.



a) Position error



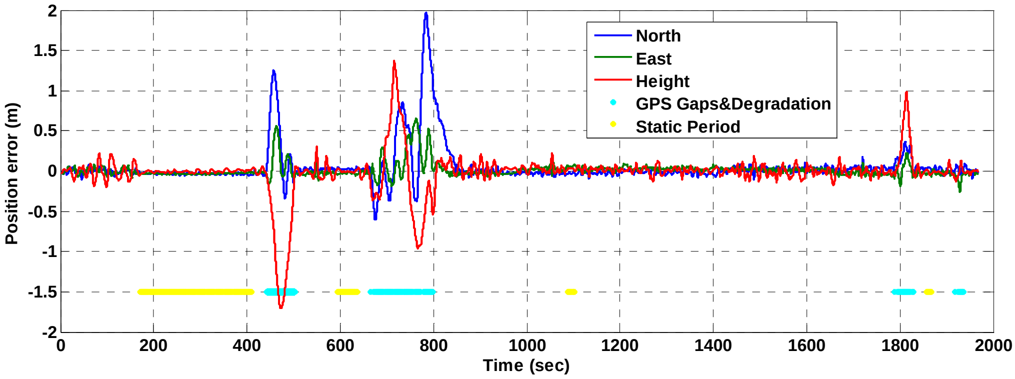
b) Attitude error

Figure 4 Navigation error of the forward filtering

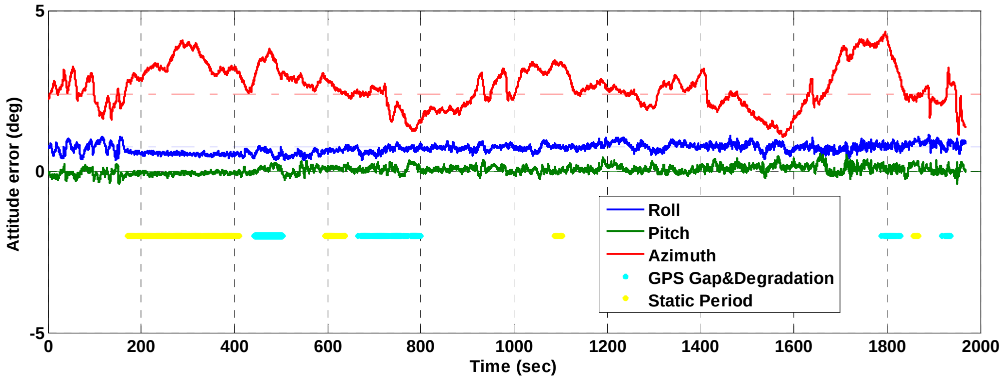
3.3.2 Backward Smoothing

As mentioned at the beginning of this section, backward smoothing can improve the navigation performance significantly, since it makes full use of the information during the whole test. Figure 5 shows the results when backward smoothing is applied. When compared to the results in Figure 4 it is obvious that both position errors (especially during GPS signal outages) and attitude errors (especially the azimuth) are dramatically reduced. The maximum position error in GPS outages and degradations is reduced from 50m to 2m. The RMS azimuth error is reduced from 1.5 deg to 0.6 deg (after removing the misalignment angles to the reference CIMU), while the maximum azimuth error is reduced from 6.5 deg to 1.6 deg (in the static period from 172s to 410s).

Although the system performance is significantly improved by backward smoothing, the azimuth error still wandered around in a range of +/- 1.6 deg, affecting by the vehicle kinematics. This is still too large as from mobile-mapping georeferencing.



a) Position error



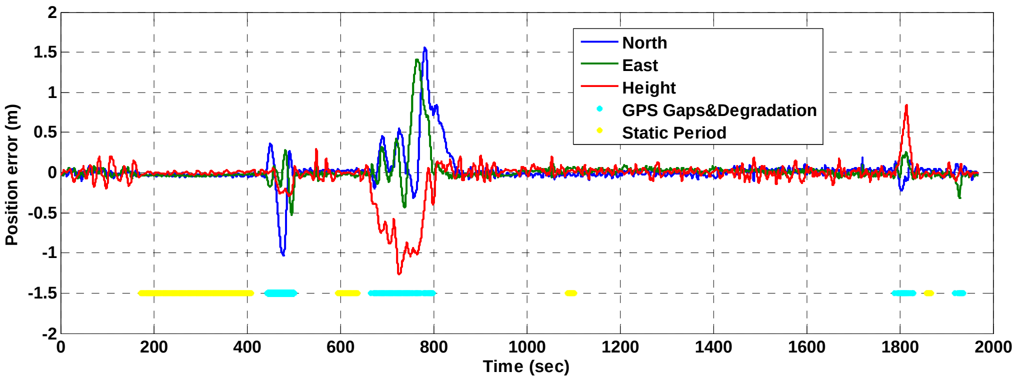
b) Attitude error

Figure 5 Navigation error of the backward smoothing

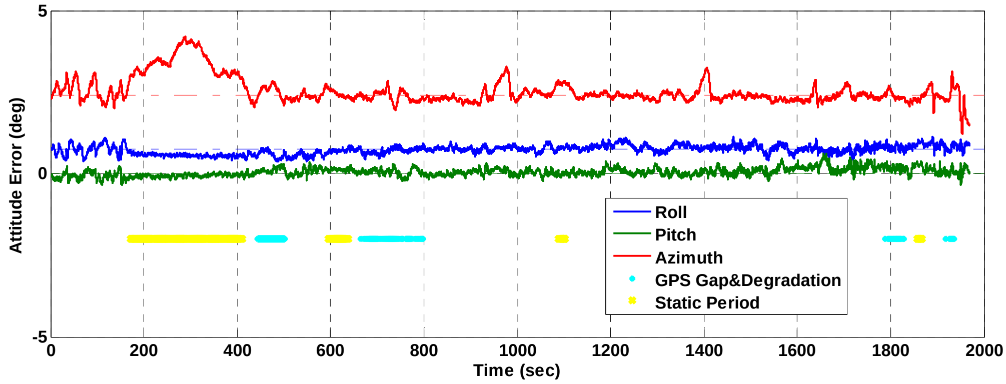
3.3.3 Backward smoothing with non-holonomic constraints

Non-holonomic constraints are stochastic constraints that limit the velocity of the vehicle in the plane perpendicular to the forward direction (Sukkarieh 2000; Shin 2001). In a land vehicle traveling on smooth roads, this velocity should be almost zero. Analysis and results have shown that such constraints suppress both the position drift along lateral direction of the vehicle in GPS outages and degradations, and the azimuth error by improving the observability of the azimuth (Niu and El-Sheimy 2005).

Figure 6 shows the smoothing results after applying non-holonomic constraints. Compared with the azimuth error to Figure 5, the RMS error is reduced from 0.6 deg to 0.35 deg. The position drift during GPS signal outages also reduced. Such accuracy is suitable for georeferencing of mobile-mapping systems.



a) Position error



b) Attitude error

Figure 6 Navigation error of the backward smoothing (applying non-holonomic constraint)

Table 1 summarizes the processing results of the MEMS-based INS/GPS navigation system. Obviously, the backward smoothing with non-holonomic constraints offers the best position and attitude estimation. Therefore, this processing strategy will be used for the georeferencing in the simulations in the following sections. Under the good testing conditions, i.e. with stable GNSS update and regular vehicle kinematics, the MEMS navigation system can offer the georeferencing information with RMS position accuracy of 0.05m and attitude accuracy of 0.35 deg.

Table 1 Navigation performances of MEMS system using different processing strategies

	Forward filtering	Smoothing	Smoothing with non-holonomic constraints
Position accuracy (RMS) with stable GPS update	0.1 m	0.05 m	0.05 m
Maximum position drift in GPS gaps and degradations	50 m	2.0 m	1.5 m
Attitude error in general (RMS)	1.5 deg	0.6 deg	0.35 deg
Maximum attitude drift with absence of kinematics	6.5 deg	1.6 deg	1.6 deg

4 DYNAMIC BORESIGHT AND LEVER-ARM CALIBRATION

As previously stated, the accuracy of any mobile mapping system depends mainly on three elements: the navigation accuracy, the inter-sensor calibration accuracy, and the imaging configuration. This section addresses the second of these factors: i.e., the inter-sensor calibration accuracy. Inter-sensor calibration refers to the technique of determining the position and attitude offsets between the navigation sensors and the cameras. The position offset is commonly termed the lever-arm, while the attitude offsets are typically referred to as the boresight angles.

The lever-arm and boresight angles are essentially determined by comparing the photogrammetrically derived positions and attitudes with INS/GNSS derived positions and attitudes. Focusing on the IMU only, it is obvious that an accurate calibration requires accurate attitude angles. With high-grade IMUs, it is possible to accurately orient (align) the IMU in static mode using a two-step process. First, accelerometer leveling is used to estimate the roll and pitch angles based on the x and y accelerometers output. Second, the azimuth angle is estimated based on the sensed components of the earth's rotation as measured by the x and y gyroscopes. Unfortunately, in a MEMS-based IMU the earth rotation signal is below the MEMS gyroscopes' noise level. Thus, this second step cannot be performed, and instead dynamic, on-the-fly alignment using the GNSS position/velocity update is required. Moreover, even once the alignment is performed, the MEMS navigation systems experiences large attitude drift if the system is in a static mode (i.e. absence of kinematics in the previous section), and so dynamic alignment followed by stationary image capture is also not an option.

Based on the above discussion, the inter-sensor calibration of terrestrial MEMS-based mobile mapping systems cannot be done in static mode as is conventionally done with mobile mapping systems based on high-grade IMU units. An alternative dynamic calibration method is instead required.

4.1 Methodology

The basic concept behind the dynamic calibration of MEMS-based mobile mapping systems is to determine the inter-sensor position and attitude offsets using images captured while the vehicle is moving. By doing so, the problems with stationary attitude angle determination and drift are avoided. Superior attitudes recovered, making use of the attitude enhancement during the periods of system dynamics.

The technique of dynamic calibration is proven using a "hybrid" simulation based on real navigation data and simulated control and image measurements. The CIMU navigation solution (both position and attitude) is used as the reference signal to simulate the image measurements of the control points. A test site (shown in Figure 3) of 60m length is selected for the calibration. For the simulation, the site was selected by comparing the MEMS attitude with the reference and choosing a site with relatively good attitudes. During the actual implementation, the vehicle should experience high dynamics before approaching (and after passing) the calibration site by horizontal maneuvering and/or linear acceleration if applicable.

68 control points are simulated at the calibration site at a distance of 20m to the left and the right of the vehicle's path. Images are simulated every 8m, corresponding to 0.4s as the vehicle velocity is around 20m/s. The VISAT camera configuration was used, although only the two cameras facing 45° inwards were used in the simulation. The control points are projected to the images based on the reference trajectory and the image measurements are contaminated with randomly generated noise of 0.5 pixels standard deviation. The control points, their corresponding image measurements, and the MEMS navigation solution are combined in a simultaneous least squares adjustment in which the boresight angles and level-arm components are estimated as parameters. The adjustment/simulation software developed in Ellum and El-Sheimy (2005) is used to simulate image measurements and to estimate the calibration parameters.

4.2 Results

Table 2 shows the results of the simulated boresight angle and lever-arm calibration. The "true" boresight angles and lever-arms were determined using the known angular and position offsets between the CIMU and MEMS IMU. In general, for both the lever-arm and boresight angles the dynamic calibration method performed quiet well. For instance, the boresight angles were approximately 8 arcmins in error. At an object distance of 20m, this corresponds to only a 0.04m error in position. Of some concern are the boresight angle standard deviations reported by the adjustment, they appear to be too optimistic when compared with the actual errors. One cause of this, however, may be the uncertainty in the angular offsets between the CIMU and MEMS IMU used to derive the true boresight angles.

Table 2 Inter-System Calibration Results

	Left Camera			**Right Camera**		
Estimated lever arm	-0.800m	0.023m	0.170m	1.350m	0.028m	0.716m
Estimated std. dev.	0.005m	0.018m	0.004m	0.005m	0.019m	0.005m
True lever arm	-0.799m	0.000m	0.163m	1.351m	0.000m	0.714m
Calibration error	0.001m	0.023m	0.007m	0.001m	0.028m	0.002m
Estimated boresight angles	-89°13'59"	42°37'58"	178°50'35"	-90°56' 1"	-47°22'30"	178°44'58"
Estimated std. dev.	1'57"	1'11"	2'6"	2'31"	1'16"	2'36"
True boresight angles	-89°18'46"	42°29'44"	178°58'58"	-90°49' 6"	-47°29'41"	178°53'23"
Calibration error	4'47"	8'14"	8'23"	6'55"	7'11"	8'25"

5 MAPPING USING MEMS-BASED GEOREFERENCING

Based on the calibration results obtained from the simulated dynamic calibration test, two independent checks have been performed to test the accuracy of the mapping based on MEMS navigation solution. The check sites are selected to tests the mapping accuracy under different conditions of GPS availability. In site I, Figure 3, good GPS signals were available and the navigation solution accuracy was better than 10 cm for the position and 0.1° for the attitude. In contrast, site II, Figure 3, had two adjacent 30 second GPS outages. The accuracy of the navigation solution in this site was approximately 1m for the position and 0.2° for the attitude.

The evaluation of the MEMS georeferencing performance is based on simulated check points with a maximum object distance of 20 m from the cameras. Image measurements of the check points were generated using the CIMU reference solution. The image measurements, the calibration parameters from the previous section, and the MEMS navigation solution were then used to estimate the coordinates of the check points using a simple space-intersection. The estimated coordinates of the check points were compared to the true values, with the results being shown Table 3. These results are based on 64 and 122 check points for sites I and II, respectively.

Table 3 Mapping Accuracies

	Site I		**Site II**	
	RMSE (m)	Abs. Max. (m)	RMSE (m)	Abs. Max. (m)
X	0.071	0.145	0.218	0.498
Y	0.042	0.114	0.286	0.595
Z	0.065	0.124	0.229	0.455
3-D	0.105	0.189	0.426	0.887

The results in Table 3 are surprisingly close to the results obtainable from high-grade IMU-based MMS. However, it should be noted that image measurements from up to 5 images were used to estimate the check point positions. Thus, the MEMS-based attitude errors may have been substantially reduced by averaging. Also, the short camera-to-object-space distance (20m) limits the effect of even a substantial attitude error.

6 SUMMARY AND CONCLUSIONS

In this paper, the idea of using a MEMS-based INS/GNSS integrated system as the direct georeferencing source of a mobile mapping was investigated using real INS/GNSS signals and simulated image measurements. The different processing strategies for integrating MEMS INS/GNSS sensory data were presented and analyzed. The positive influence of backward smoothing on the results enhancement was highlighted. Based on a hybrid simulation, the dynamic system calibration showed promising results. A mapping simulation showed how the mapping accuracy of the MEMS system can reach a couple of decimeters level when the satellite signals are available. In case of GNSS outage for periods of range 30s, such system can deliver accuracies around 1m. The mobile mapping system based on MEMS IMU can be used successfully for surveying rural highways, and the urban roads without intensive high buildings surrounded. The future work will include the proof of both the dynamic system calibration and mapping accuracies using real image georeferenced by MEMS based IMUs.

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BIOGRAPHICAL NOTES

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