Multisensor System for Automatic Monitoring of Highway Linear Features

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ABSTRACT

During the last decade of the 20th Century the concept of Mobile Mapping Systems (MMS) has been established and evolved from rather simple land-based systems to more sophisticated, real-time multi-tasking and multi-sensor systems, operational in land and airborne environments. Mobile Mapping technology has made remarkable progress, notably expanding its use in remote sensing, and surveying and mapping markets. New systems are being developed and built for specialized applications, in support of land-based and airborne imaging sensors, aimed at automatic data acquisition for GIS databases.

The major objective of this paper is to present a new GPS/INS/CCD integrated system for precise monitoring of highway center and edge lines. The system has been developed at The Ohio State University for the Ohio Department of Transportation. The prototype of the positioning component of the system is based on a tightly integrated GPS/INS (Trimble 4000SSI, Litton LN100), and the imaging component comprises a fast, down-looking, color digital camera from Pulnix (TMC-6700, based on 644 by 482 CCD and acquisition rate up to 30 Hz). The high image rate provides sufficient overlap of the subsequent images at highway speed; therefore stereo data processing can be performed in near real time with the support of a single camera and on-the-fly navigation solution.

In this paper, we discuss the design, operational aspects and performance analysis of the system prototype. A new approach to the application of navigation data to real-time processing of the imagery is also presented. In particular, a performance analysis of the georeferencing module, based on extended field tests, will be discussed.

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1. INTRODUCTION

The mobile mapping system (MMS) presented in this paper is designed for high-accuracy mapping of highway center and edge-lines (Grejner-Brzezinska et al., 2001a and b; Toth and Grejner-Brzezinska, 2001a and b). The system's prototype was developed at the Ohio State University, for the Ohio Department of Transportation (ODOT). The system consists of three major modules: (1) real time control and data acquisition, (2) positioning, and (3) imaging.

The primary objective of the control module is to support real-time data acquisition and system controls, such as number of satellites in view and PDOP (position dilution of precision), primarily for real-time QA/QC (quality assurance and quality control). This is a very important aspect of any MMS, especially those operating in urban environments. Frequent losses of lock may occur in urban canyons, while the vehicle travels on a busy highway or under bridges/overpasses, etc., causing a decrease in positioning accuracy. To prevent serious losses of accuracy, the control system tracks the PDOP and the duration of the loss of lock (or extended partial satellite blockage), and, based on empirical knowledge of the positioning error growth, it provides a warning to the operator that ZUPT (zero velocity update) is needed. Performing a ZUPT calibration of the system will significantly reduce the increase of positioning errors during the free inertial navigation (Grejner-Brzezinska et al., 2001a and b).

The positioning module of this system is based on a tight integration of dual frequency differential GPS phases and raw IMU data provided by a medium-accuracy and high-reliability strapdown Litton LN-100 inertial navigation system. LN-100 is 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). An optimal 21-state centralized Kalman filter estimates errors in position, velocity, and attitude, as well as errors in the inertial and GPS measurements. The primary filter design follows the concept of AIMS™ (Grejner-Brzezinska et al., 1998; Toth and Grejner-Brzezinska, 1998), developed earlier, which has been modified and extended to accommodate needs of precision navigation in urban environments. Under favorable GPS constellation (minimum of 5-6 satellites), the estimated standard deviations are at the level of 2-3 cm for position coordinates, and ~10 arcsec and 10-20 arcsec for attitude and heading components, respectively.

The imaging module consists of a single, down-looking, color digital camera, Pulnix TMC-6700, based on 644 by 482 CCD, with an image acquisition rate of up to 30 Hz, which allows for 60% image overlap at normal highway speed (footprint size is about 6.68 by 2 m; see Table 1). More details are provided in (Grejner-Brzezinska and Toth, 2000; Toth and Grejner-Brzezinska, 2001 a and b). The imaging system provides a direct connection between the vehicle georeferencing (positioning) module and the road marks visible in the imagery, allowing the transfer of the coordinates from the reference point of the positioning system (center of the INS body frame) to the ground features. Naturally, calibration components, including camera interior orientation (IO), as well as INS/camera boresight calibration components are needed (see, for example, Grejner-Brzezinska, 2001). To assure 3D image processing, a 50-60% overlap is needed along the vehicle motion; this is easily achieved with the hardware implemented in our system. Stereovision is realized by the platform motion, which, in turn, emphasizes the need for high-precision sensor orientation provided by direct geo-referencing (positioning module). The ultimate performance analysis of the positioning component and the integrated positioning/image module are presented in the sequel.

2. OPERATIONAL ASPECTS OF MMS FOR CENTERLINE/EDGE LINE EXTRACTION

The level of automation of the image sequence processing in a typical MMS can vary depending primarily on the content of the imagery and the scale variation. The more variation in the image scale and the richer the image content, the more difficult the task of automated feature extraction (Habib, 2000). Typically, even in post processing the feature extraction task requires substantial user interaction. Since our system uses a down-looking camera, with an image sensor plane almost parallel to the road surface, the image scale changes are negligible, thus an almost constant scale along the vehicle trajectory can be maintained. Moreover, the object contents of the images are rather simple and predictable, such as the line marks, surface texture variations, cracks, potholes, skid marks, etc. Consequently, extracting features from a predefined set of objects, assuming almost constant image scale, represents a less challenging scenario, as compared to the generic MMS paradigm, where the scale variations (and the richness of features) pose serious difficulty for any automated feature extraction task. System design and image sequence processing are presented in detail in (Toth and Grejner-Brzezinska, 2001a and b). In this paper, only a brief overview of the system's operational aspects is presented. Table 1 summarizes the camera characteristics and the image acquisition conditions, while Figure 1 illustrates the system architecture.

Camera CCD pixel size	9 micron
Camera focal length	6.5 mm
Camera height above road surface	3 m
Image scale	3/0.0065=461
Ground pixel size at nadir (no tilt)	4.1 mm
Ground coverage along vehicle	2.68 m
Ground coverage across vehicle	2 m
Maximum speed without overlap	2.68/0.1=26.8 m/s (96 km/h or 60 MPH)
Maximum speed to maintain 50% overlap	26.8/2 m/s (48 km/h or 30 MPH)

Table 1. Sensor characteristics and the image acquisition conditions.

As already explained, real time image processing is technically feasible due to simple sensor geometry and the limited complexity of the imagery collected (single down-looking camera acquiring consecutive images with about 50% overlap). First, color transformation and filtering are applied to the raw images; next by applying object space geometrical constraints, the centerline can be extracted. Namely, feature points are extracted around the centerline area, and are subsequently used for image matching. Consecutive images are connected this way, and consequently a strip of images is built. This process will ultimately be performed in real time; however, the results of the tests presented here have been obtained in post-processing. It should be mentioned here that we are entering the fine-tuning stage of the system, where the post-processing results will allow us to identify the processing steps that need to be adapted to a real-time scenario. The major objective is to provide a robust solution with the capability to recover from possible losses of data, and to achieve it under the acceptable CPU load. We apply the iterative correction scheme, which has already resulted in a substantial decrease in execution time. It is expected that by beta testing, the adaptability of the system can be further improved, resulting in a better real-time performance. It should also be noted that besides the anticipated need for more software engineering (code optimization), some implementation difficulties are directly related to the behavior of the operating system (Windows 2000).

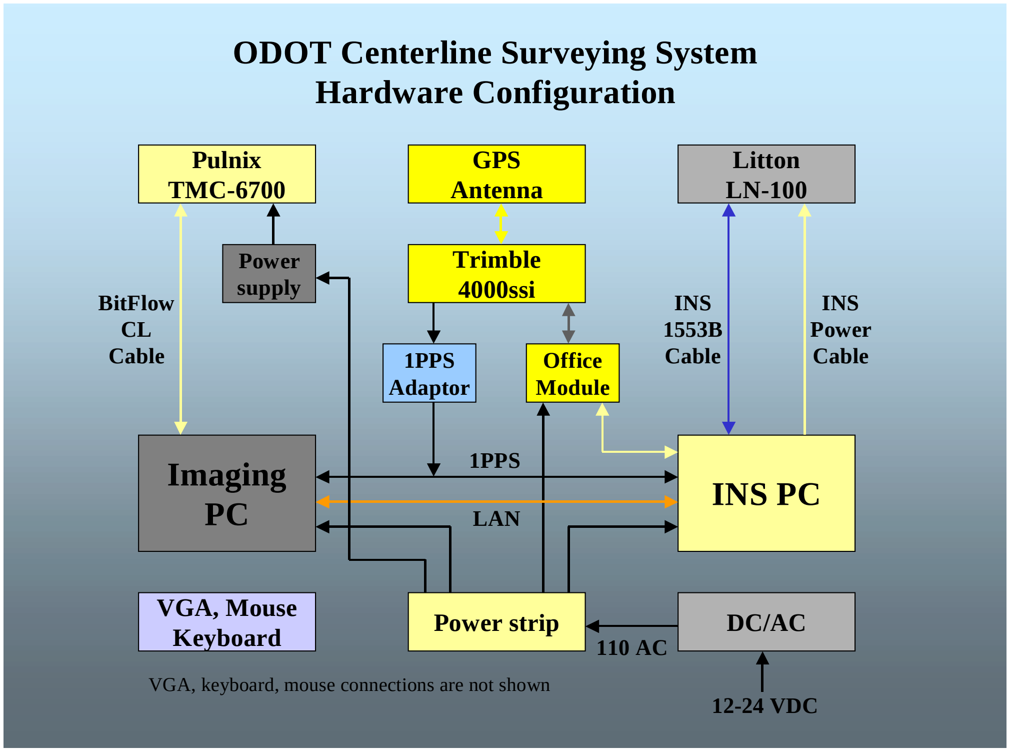


Figure 1. MMS design architecture and data processing flow.

The image matching process (either in real time or post-processing) is greatly enhanced if the image orientation data are available. In essence, availability of the relative orientation between the two image captures dramatically decreases the search time for conjugate entities in the image pairs, since the usually 2D search space can be reduced to one dimension (along the epipolar lines). The first step in the image matching is to identify feature points in the left image. The search for the matching counterparts in the right image exploits the epipolar geometry. If the true orientation is known, the search for a conjugate point, matching the one in the left image, is carried along the corresponding epipolar line in the right image. However, errors in orientation data introduce an uncertainty in the location of the epipolar line, stretching it to an epipolar band, as shown in Figure 2, for an accuracy of 0.1 cm and 0.1°, respectively. Naturally, searching along a line is much faster than along a bundle of lines, and the wider the band the longer the search time. Table 2 compares the execution times for 20 feature points extracted and matched on a dual Pentium 4 at 1.7 GHz. (Toth and Grejner-Brzezinska, 2001a).

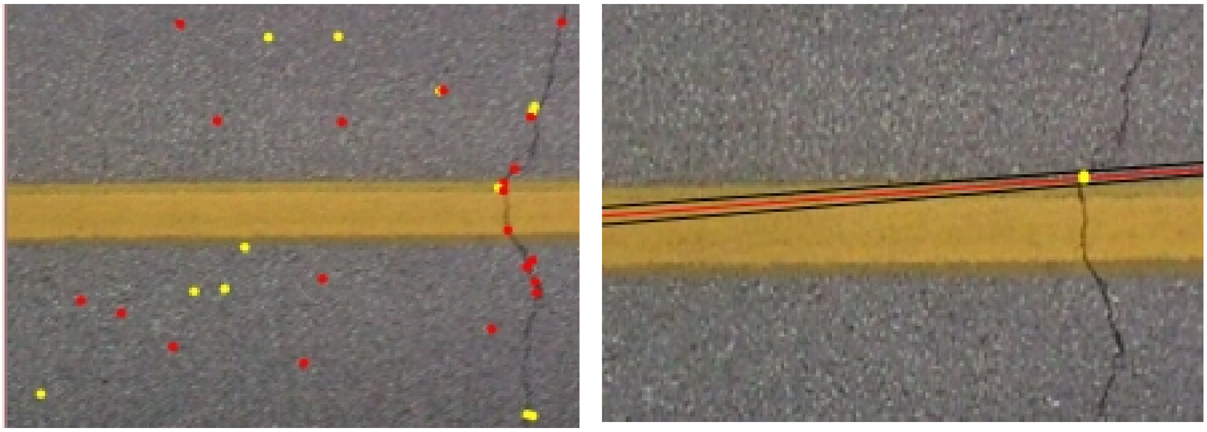


Figure 2. Feature points extracted from one image and matched to overlapping image, in red (left), and epipolar line and band (right).

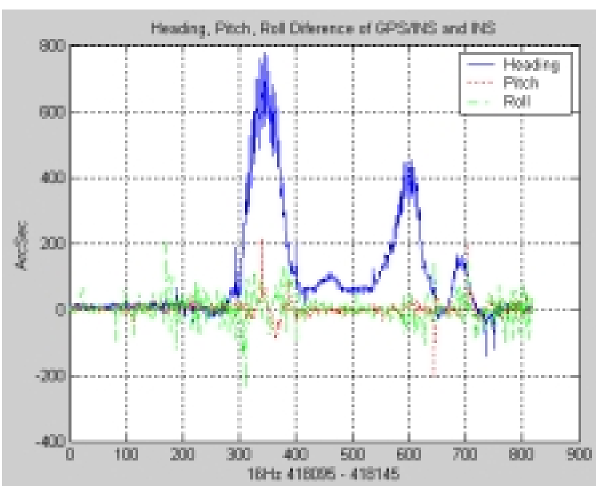
Task	**Relative orientation accuracy in position and attitude**		
	3 cm and 0.5°	**0.5 cm and 0.1°**	**0.1 cm and 0.01°**
Feature point extraction [s]	0.04	0.04	0.04
Matching [s]	0.22	0.008	0.003
Total [s]	0.26	0.048	0.043
Max image rate [Hz]	4	21	23

Table 2. Execution time as a function of the accuracy of relative orientation.

The main goal of the on-the-fly (OTF) image processing is to determine the centerline image coordinates in real time (using real time navigation data), so that only the extracted polyline, representing the center/edge lines would be stored, without a need to store the entire image sequence. Conceptually, this process allows determining the image coordinates of the points at the required accuracy level, while their object space coordinates are very coarse. Consequently, the final, refined object space coordinates will be determined during post-processing once the final GPS/INS solution becomes available. Thus, in this image processing paradigm, the absolute accuracy of the real time navigation data is not that critical, primarily due to the rather large photo scale (see Table 1) and the fact that the real-time processing is only concerned with relative motion estimates (relative orientation). However, absolute GPS/INS accuracy is crucial for refining the strip orientation in post-processing. The analysis of the real-time navigation information from the standpoint of the required quality for real-time image processing (quality of relative orientation) is presented in great detail in (Toth and Grejner-Brzezinska, 2001a and b). In this paper, only the major issues are briefly addressed.

2.1. Achievable accuracy of the relative orientation in real time

To support the image matching and linear feature extraction OTF (as the project's ultimate goal), the performance of the on-the-fly navigation is of major interest. The positioning accuracy of an INS in free navigation mode decreases with time, as the IMU sensor errors grow. Thus, the long-term accuracy of INS is rather low (from the mapping standpoint), and depends on the quality of the IMU sensors (for example, good quality INS, such as LN100 is a 0.8 nmi/h system). However, the change in the position and attitude of the camera (determined by free navigation mode) between the two image captures is not affected by long-term trends, as the time difference between the events is very short. A typical image capture rate is about 10 Hz, so position and attitude changes, or rather the change in their error estimates at 0.1 s, are of main concern to our system. In our analysis, the difference between the free navigation solution and the GPS/INS solution is considered a measure of error of the free navigation. In practical terms, if two subsequent images are similarly misoriented (i.e., contain a similar amount of error) with respect to the reference solution (GPS/INS), then the stereo reconstruction should be achievable. Thus, the two images have a good quality relative orientation, but still might be misoriented in absolute terms, which can be rectified in post-processing. Figure 3 shows the differences in the image orientation, and the corresponding rate of change of these differences. Figure 4 illustrates typical differences observed between the post-processed GPS/INS and free navigation mode coordinates, and the corresponding rate of change of these differences. Our preliminary tests (assuming the use of high power Pentium 4 processors) indicate that the amount of error in relative orientation as displayed in the figures below (typical situation) should support real time image matching with sufficient accuracy. In particular, with an image separation of about 1.3 m (overlap), the error in relative orientation of about 50 arcsec will translate to an ~0.3mm linear offset, which is negligible; thus the error in the linear component of relative orientation has more impact on the image matching speed and efficiency.



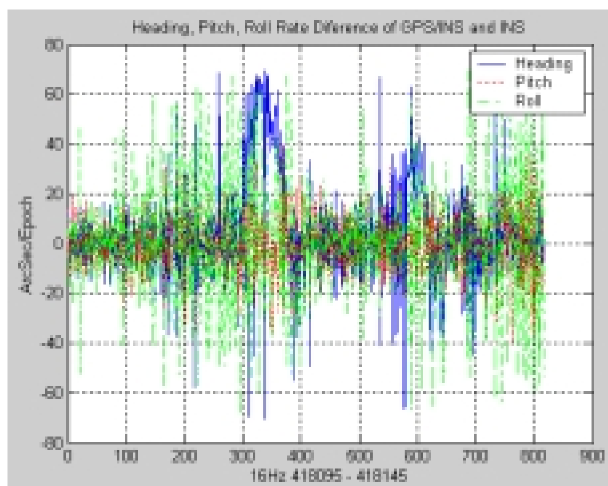


Figure 3. Difference between post-processed and free navigation mode attitude angles (left) and the corresponding rate of change of attitude differences (right); the largest picks correspond to the sharp turns of the vehicle

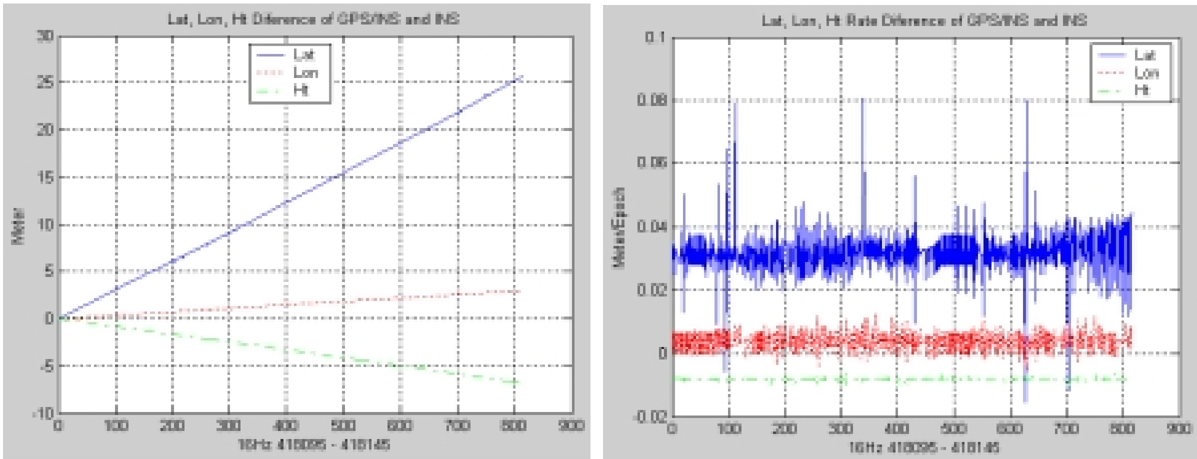


Figure 3. Difference between post-processed and free navigation coordinates (left) and corresponding rate of change of positional differences (right).

3. POSITIONING ACCURACY OF THE NAVIGATION MODULE (POSTPROCESSING)

The details related to the design, operational aspects and performance analysis are presented in (Grejner-Brzezinska et al, 2001a and b). In this paper, we present only a brief overview of the navigation module, with a special emphasis on the quality of positioning during partial or total GPS blockage, performance of the ZUPT module, and possible enhancement to the system through the use of pseudolites.

3.1. Effect of ZUPT calibration on positioning accuracy and ambiguity resolution

The accuracy of the feature positioning in the object space achievable by our system can reach a few centimeters, when the number of GPS satellites amounts to six and above (Grejner-Brzezinska et al., 2001a). However, when an extended partial or total signal blockage occurs, the system's accuracy can drop rather significantly. To prevent an excessive decrease in the accuracy, a ZUPT module has been implemented, which facilitates the static calibration of the IMU sensor errors, allowing for a reduction in the total positioning error budget, and also supporting fast ambiguity recovery after loss of lock. The amount of positioning error accumulated during the GPS loss of lock depends on several factors: (1) the duration of the INS calibration using GPS data before the signal blockage, (2) geometry and dynamics of the portion of the trajectory used to calibrate INS errors OTF, and, naturally, (3) the extent of the gap. The more significant the geometry variations along the calibration portion of the trajectory, and the longer the calibration period, the better the sensor calibration quality, and thus the slower the positioning error growth during the free navigation mode. The effect of the calibration length is more pronounced for longer GPS gaps. Depending on the above-mentioned factors, the error growth per component can range from 1-3 cm for gaps of 30 s and long calibration times (above 200 s), to 10-30 cm for gaps of 120 s, and calibration times of ~120 s prior to the gap. These numbers correspond to the INS calibration (sensor error estimation) performed during the varying geometry of the trajectory. When calibration is performed during the straight portion of the trajectory prior to the loss of lock, these numbers can be significantly larger, especially for short calibration times (see Grejner-Brzezinska et al., 2001a and b for more details).

Thus, when the gap in the GPS signal is relatively long, exceeding 60-90 s, it is necessary to perform the static (ZUPT) calibration of INS, to prevent further error increase. It has been concluded in *ibid.* that typically during the extended losses of GPS lock, ZUPT should be performed every one to two minutes, depending on the acceptable level of error for a particular application, and the ambiguity resolution mechanism. Table 3 illustrates the impact of a 20-second ZUPT on the level of the positioning errors after 60 s of free navigation. Two cases are presented, (1) with a 20 s ZUPT following the free navigation period, and (2) without a ZUPT. The free navigation mode continued after the ZUPT in case (1), and was 140 s long in total in case (2). The positioning error was estimated with respect to the reference GPS/INS solution at the end of the 140-s period. Clearly, a ZUPT event causes a significant decrease in the positioning error growth, especially in East and North, while the improvement in height is less pronounced (the vertical channel in INS is the weakest).

Free navigation [s]	**ZUPT [s]**	**Free navigation [s]**	**Total error [m]**		
			East	**North**	**Height**
60	20	60	0.03	0.02	0.11
60	0	80	0.16	0.45	0.16

Table 3. The effect of ZUPT on the rate of the positioning error growth in free navigation.

Tables 4 and 5 describe the effects of the presence of ZUPT events on the ambiguity resolution when the GPS lock is re-established. A 4000 s GPS/INS data set, collected on January 31, 2001, with 5-6 GPS satellites in view, was used to derive the statistics presented in Tables 4 and 5 (Grejner-Brzezinska et al., 2001a). Multiple GPS gaps of 30, 60 (not shown due to space limitations) and 90 s were introduced, and the ambiguity resolution time was determined as a function of GPS/INS calibration time, free navigation mode duration, and the length of the ZUPT events (relevant only to the case presented in Table 4). However, it should be pointed out here that the ZUPT duration does not make a significant difference, as our observations indicate that any ZUPT of 10-20 s provides enough calibration time.

GPS/INS calibration [s]	**Free navigation [s]**	**ZUPT [s]**	**Check Point #**	**Ambiguities fixed within first 2 epochs [%]**	**Ambiguities fixed within 3-20 epochs [%]**	**Ambiguities fixed within 21-90 epochs [%]**
< 100	30	6-20	13	92	0	8
100-200	30	16-20	6	83	0	0
>200	30	5-20	4	100	0	0
< 100	90	8-20	8	50	0	50
100-200	90	16-20	6	83	0	17
>200	90	5-20	3	67	0	33

Table 4. Ambiguity resolution statistics supported by ZUPT.

GPS/INS calibration [s]	Free navigation [s]	Check Point #	Ambiguities fixed within first 2 epochs [%]	Ambiguities fixed within 3-20 epochs [%]	Ambiguities fixed within 21-90 epochs [%]	Not fixed [%]
< 100	30	13	62	15	8	15
100-200	30	6	83	0	0	17
>200	30	4	75	0	0	25
< 100	90	8	0	38	50	12
100-200	90	6	17	17	66	0
>200	90	3	34	33	33	0

Table 5. Ambiguity resolution statistics without ZUPT.

A comparison of Tables 4 and 5 indicates that if no ZUPT events are present before the signal reacquisition, a significantly lower number of ambiguities can be fixed within the first two epochs, as compared to the case of ZUPTs following the free navigation mode. Also, while results in Table 4 indicate that all the ambiguities were solved after 90 epochs, Table 5 still shows some percentage of unresolved ambiguities. In general, the longer the free navigation mode (especially the one not supported by ZUPT), the more time is needed to fix the ambiguities. This is rather obvious, as for longer gaps more error is accumulated in the free navigation mode, whose positioning results are used to estimate the approximated ambiguity for the search procedure, or, if the gap was short and the ZUPT was performed, the actual ambiguities can be found without any search process.

3.2. Effect of pseudolite on positioning accuracy

The system's positioning module has been recently extended by integrating a pseudo-satellite (pseudolite, PL) signal. Thus, the positioning Kalman filter currently operates on INS, GPS and PL data. Even though the tests to date were performed with only a single PL, the system can easily be extended to receive the data from multiple PLs. Pseudolites are ground-based transmitters, which send a GPS-like signal to support positioning and navigation in situations where the satellite constellation may be insufficient. They are usually located on building rooftops, specialized poles, or any high location in the vicinity of the survey area, resulting in a relatively low elevation angle, as compared to GPS satellites. However, even the signal from a low satellite (PL) should strengthen the geometry of position determination, especially in the height direction. An additional GPS-like signal may also support the process of ambiguity resolution. The majority of pseudolites transmit GPS-like signals on L1 (1575.42MHz) and possibly on L2 (1227.6MHz) frequencies. Thus, with the modification of the firmware, standard GPS receivers could be used to track PL signals. It should be mentioned that PL signal could potentially interfere with the satellite signals due to the fact that the PL transmitter is very close to the receiving antenna, as compared to the GPS satellites (the near-far problem). The solution to this problem is to pulse the PL signals at a fixed cycle rate, or apply a frequency offset (e.g., 1MHz from L1), or the signal power control. Pseudolites can be designed to receive and transmit ranging signals at GPS L1/L2 or other frequencies (transceiver), and thus can be used to self-determine their own locations (for more information on pseudolites see, for example, Elrod and Van Dierendonck, 1996; Hein et al., 1997).There are a few possible problems related to the use of pseudolites; among

them: (1) any errors in the PL location will have a significant impact on the receiving antenna coordinates due to the short distance between the receiver and the PL, (2) since the PL is stationary, its location bias is constant, and its effect on position coordinates of the receiver depends on the geometry between the PL and the receiver, thus the RDOP (relative dilution of precision) should be studied before selecting a location for the PL, (3) bad geometry may cause singularity in the solution, (4) special attention must be exercised towards an appropriate modeling of the tropospheric effects (different models from those used for the GPS signal must be applied), (5) possible strong multipath signature of the PL signal (low elevation angle), which may come from the transmitter itself, not only reflecting objects, (6) differential technique will eliminate fewer error sources, as opposed to regular DGPS, due to totally different geometry; consequently, the PL location error or tropospheric effects will not cancel with double differences, as the geometry is not identical for the mobile user and the reference station (for longer baselines).
In the test presented here, one single frequency (L1) pseudolite, IN200CXL, manufactured by IntegriNautics Inc., and two NovAtel GPS receivers OEM MILLENRT2 from the University of New South Wales were used, together with LN100 INS, on May 4, 2001. The test was performed at the OSU West Campus area; a PL was located on the top of a tall building (Lincoln Tower), resulting in elevation angles between 7 and 13°, depending on the vehicle location. During the test, 5-6 GPS satellites were observed, during a total of 3899 time epochs (1Hz data rate); 1030 epochs were missing PL data either due to signal obstruction or higher noise level (data rejected by the filter). The mean residual from double differences including PL observation was –0.001 m, indicating no significant bias in the solution. Figure 7 illustrates the RDOP comparison between the solutions with and without the PL, and the difference in the positioning results between the two solutions.

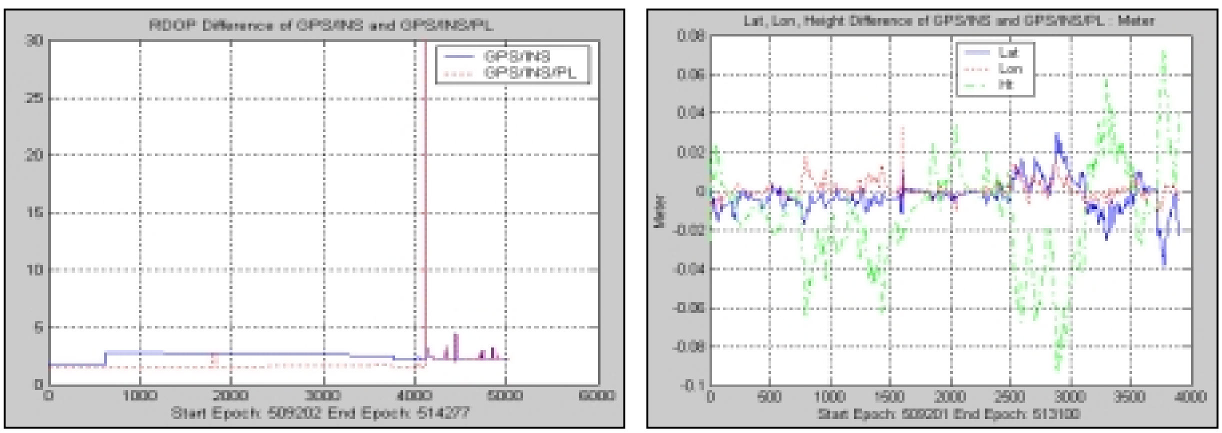


Figure 7. The RDOP plots for solutions with and without PL (left), and the difference in the positioning results between the two solutions (right).

4. PERFORMANCE ANALYSIS BASED ON REFERENCE GROUND TRUTH

The georeferencing performance of the system was tested using ground control points. In the analysis presented here, only the final positioning performance is addressed, while the automated image sequence processing was not considered (thus, post-processing of images was used). First, the images were collected over the 10-point calibration range located at the OSU West Campus and along the service road. The test range points have a 10 m separation, and were located by GPS with 1-2 cm accuracy. The images over the test range were used to determine the boresight calibration between the INS and camera frames. Aerotriangulation (AT) was performed on an image block containing four points of the range. Final AT accuracy was 20 mm, 22 mm and 13 mm for x, y and z, respectively, 0.5° in pitch and roll, and 0.3° in heading. An independent GPS/INS solution provided the coordinates for INS body frame center, with accuracy of 1-2 cm and 8-10 arcsec for pitch and roll, and 15-20 arcsec for heading. Comparison of the AT and GPS/INS solutions provided the boresight transformation offsets and angles (Grejner-Brzezinska, 2001b). The boresight offsets were -0.513 m, 0.022 m and 0.050 m in x, y and z INS body directions, respectively, and the angular components were: -0.88605°, 12.54681°, and 88.26535° in roll, pitch and heading, respectively. Then, by applying the computed boresight transformation to the refined navigation data, the exterior orientation (EO) was computed for the other images. Using a stereo digital photogrammetric workstation, models were set based on the EO data, and checkpoint coordinates were measured by an operator. The comparison of these coordinates with ground truth is shown in Table 6.

Coordinate error	Point 1	Point 2	Point 3	Point 4	Mean	RMS
X [m]	-0.023	0.032	0.069 (0.060)	0.010 (-0.016)	0.022	0.038
Y [m]	0.027	0.050	-0.017 (-0.056)	-0.059 (-0.045)	-0.017	0.046
Z [m]	0.032	0.094	0.004 (-0.087)	-0.093 (-0.082)	-0.022	0.077

Table 6. Checkpoint fit to ground truth (points 3 and 4 were measured in two passes).

5. SUMMARY

A prototype MMS, designed for mapping the center and edge lines of highways, was introduced and its operational components were described. The positioning accuracy was presented based on the field tests and post-processing mode of operations. The ultimate goal of the system is to process the imagery in real time, using the approximated orientation data available on-the-fly. As explained earlier more software and possibly hardware optimization is needed to implement this option. The post-processing accuracy achievable with the current prototype meets the project specifications.

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BIOGRAPHICAL NOTES

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