NEAR REAL-TIME ROAD CENTERLINE EXTRACTION

C. K. Toth[1] and D. A. Grejner-Brzezinska[2]

Center for Mapping, The Ohio State University, 1216 Kinnear Road, Columbus, OH 43212-1154, USA
Department of Civil and Environmental Engineering and Geodetic Science[2], The Ohio State University
toth@cfm.ohio-state.edu

Commission III

KEY WORDS: Mobile Mapping, Image Sequence Processing, Direct Sensor Orientation, Real-Time Systems

ABSTRACT:

In this paper a new GPS/INS/CCD integrated system for precise monitoring of highway center and edge lines is presented. The system has been developed at The Ohio State University (OSU) for the Ohio Department of Transportation (ODOT). The positioning component of the system is based on tightly integrated GPS/INS (dual frequency GPS receiver and a high-accuracy strapdown INS), and the imaging component comprises a fast, color digital camera from Pulnix (TMC-6700, based on 644 by 482 CCD, with the acquisition rate up to 30 Hz), installed in a down-looking position. The high image rate provides sufficient overlap of the subsequent images at reduced highway speed. The stereo image data processing is supported in near real-time by on-the-fly navigation solution.

In this paper, we discuss the design, algorithmic solution and operational aspects, as well as the calibration and performance analysis of the developed system. Feasibility of the application of real-time navigation data to on-the-fly image processing is also presented. In particular, a performance analysis of the integrated system, based on reference ground control, is discussed.

1. INTRODUCTION

Mobile Mapping Systems (MMS) have been developed since the early 1990s with a primary focus on the acquisition of the street environment data, i.e., man-made features and their attributes along the road corridor, as well as the topography. Over the years, MMS has evolved from a rather simple, low to modest accuracy mapping system, to modern state-of-the-art multisensor systems, incorporating an increasing amount of real-time operations. Mobile computing and wireless communication are considered two of the strongest trends in the modern computer industry. The proliferation of mobile computer and wireless technology used in modern MMS, combined with multiple, high resolution digital imaging sensors, bring fundamental changes to the ways the geoinformation data are acquired and analyzed: the data can be analyzed on-the-fly, and transferred to the data centers, where they can be transformed to the intelligent georeferenced information, and subsequently distributed to the users.

The MMS presented in this paper, although classified as real time, does not fully follow the paradigm of mobile computing outlined above. The data are not transferred to the data analysis center, but rather part of the data processing is performed during the data collection, in real-time, by the onboard computer. Since the system is designed for mapping of center and edge lines of the highways, the instantaneous data transfer is not crucial. The real-time image processing is designed to limit the amount of data stored for further processing. In particular, the linear features can be extracted and tracked from the imagery on-the-fly, using real-time navigation information, which can effectively support the formation of stereo-pairs. Therefore, the real-time part of the image processing is only concerned with the relative orientation (RO). Tthe final processing can be done in post-mission mode when more precise navigation data become available. In this paper, a discussion related to the recently performed tests demonstrating the achievable accuracy in real time is included, while more details on the system design and the concept of real-time processing can be found in (Toth and Grejner-Brzezinska, 2001a and 2001b; Grejner-Brzezinska, Toth and Yi, 2001; Grejner-Brzezinska, Yi and Toth, 2001; Grejner-Brzezinska and Toth, 2002).

2. SYSTEM DESIGN AND IMPLEMENTATION

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 the errors in the inertial sensors. In addition, the basic 21-state vector can be augmented by the additional states representing GPS differential ionospheric correction terms, which are estimated (per satellite pair, as double difference mode is used) when the base-rover separation exceeds 10 km distance. 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. These augmentations primarily include the implementation of the static INS calibration (ZUPT mode) and the extension of the measurement update module to include the pseudolite data (Grejner-Brzezinska et al., 2002), as well as further processing optimization. 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. These naturally do not represent the final mapping accuracy, which can only be confirmed by an independent comparison with the ground control, as presented in Section 6. Figure 1 illustrates the system architecture (Cairo or Budapest Grejner-Brzezinska and Toth, 2002), and Figure 2 presents the prototype hardware configuration.

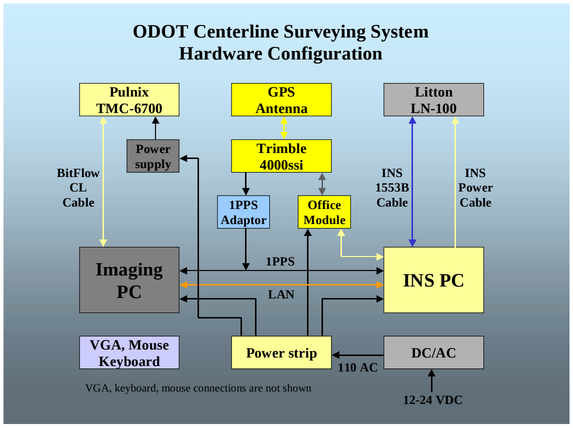

Figure 1. Design architecture and data processing flow.

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
Max speed, no overlap at 10 FPS	26.8 m/s (96 km/h)
Max speed at 50% overlap	13.4 m/s (48 km/h)

Table 1. Sensor characteristics and the image acquisition parameters.

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 (10 Hz is the target for our application), which allows for full image coverage at normal highway speed or 50% image overlap at reduced speed (footprint size is about 2.68 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 for 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 the camera interior orientation (IO), as well as INS/camera boresight calibration components are needed (for algorithmic details see, for example, Grejner-Brzezinska, 2001). For 3D image processing, a 50-60% overlap is needed along the vehicle motion, which can be 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 georeferencing. Table 1 summarizes the camera characteristics and the image acquisition conditions.

ODOT District 1 office built the complete system with all the sensors and supporting hardware installed in early 2002 and Figure 2 shows the surveying vehicle.

Figure 2. Mapping vehicle.

3. IMAGE SEQUENCE PROCESSING CONCEPT

There are two key questions regarding the development of the image sequence-processing concept. The first is whether a more complex stereo model-based technique or a simple monoscopic method should be used for the centerline position extraction process. Second is the question of whether a completely real-time (or near real-time) solution implementation should be considered or whether post-processing should remain the only option. The main goal of on-the-fly image processing is to determine the centerline image coordinates in real time, so that only the extracted polyline, representing the center/edge lines, would be stored without a need to store the entire image sequence. Clearly, there is a strong dependency among these options and the decision was made at the beginning to develop the system with full 3D capabilities in a possibly real-time implementation. Later, based on the initial performance, the design may be modified. In simple terms, the stereo processing can provide excellent accuracy but it imposes more restrictions on the data acquisition process, such as the need for continuous image coverage with sufficient overlap, and it definitely requires more resources. The single image solution however, is a compromise in terms of accuracy but it is very tolerant toward the image acquisition process, e.g., gaps will not cause any problems and the processing requirements are rather moderate.

The real-time image processing is technically feasible due to the simple sensor geometry and the limited complexity of the imagery collected (single down-looking camera acquiring consecutive images with about 50% overlap; only linear features are of interest). The most challenging task is the extraction of some feature points around the centerline area, which can be then subsequently used for image matching. Note that the availability of the relative orientation between the two consecutive images considerably decreases the search time for conjugate entities in the image pair, since the usually 2D search space can be theoretically reduced to one dimension, along the epipolar lines. However, errors in orientation data introduce some uncertainty in the location of the epipolar line, stretching it to an epipolar band, whose width depends on the accuracy of EO parameters. The overall image sequence processing workflow, including the real-time components as well as the post-processing part, is shown in Fig. 3. For the single image approach, the buffering of the previous image and the complete stereo processing module can be omitted.

The above design was initially prototyped in Matlab and since then has been implemented in Visual C++ environment. The low-level image processing steps that are identical for both stereo and single image processing are discussed in detail in the Cairo paper; here there is only the end result of the processing shown in Figure 4, illustrating the robustness of the method on a rather difficult road surface.

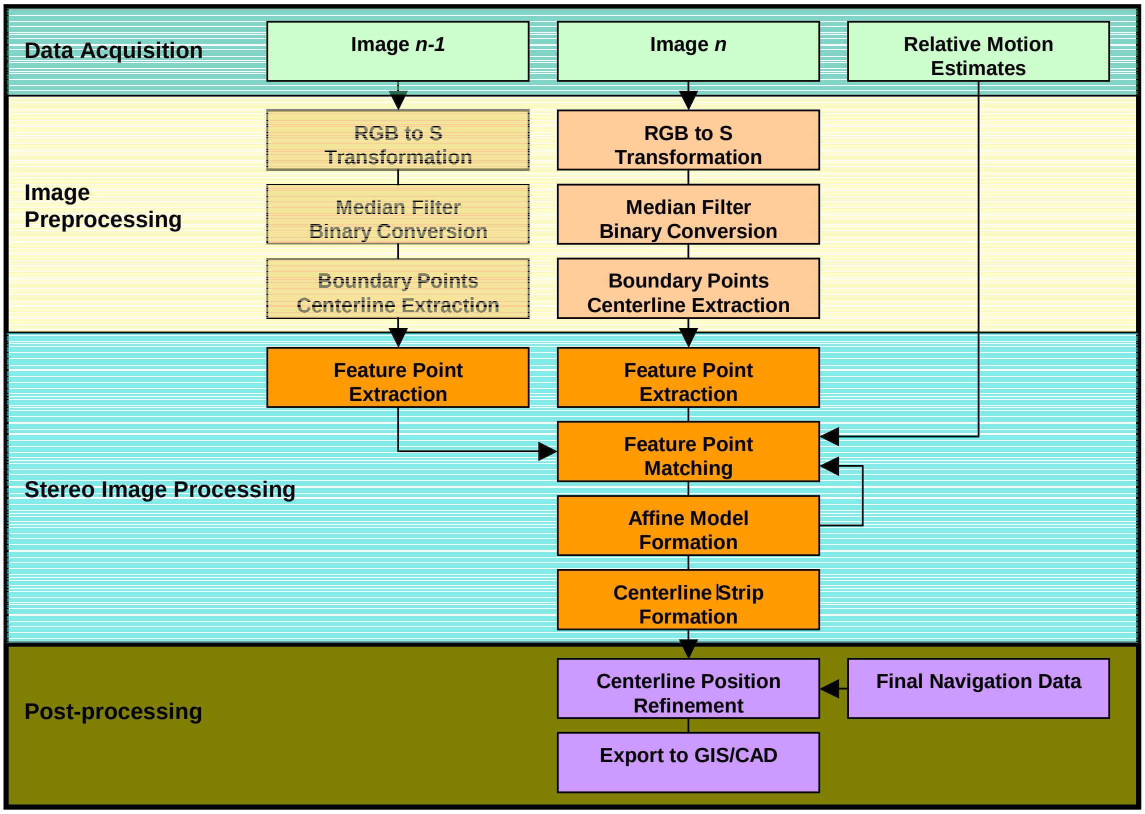

Figure 3. Real-time image processing and post-processing workflow.

To assess the feasibility of the real-time image sequence processing in stereo mode, several simulations as well as real tests were performed. For example, for real-time EO parameter accuracy of 3 cm and 0.5° respectively, the image matching based on a 20 feature point model, executed on a dual Pentium 4 at 1.7 GHz is about 0.26 s, allowing for a maximum image rate of 4 Hz, while errors in EO of 0.5 cm and 0.1°, respectively, allow for image rate of 21 Hz, since the total image matching time is only 0.048 s (Toth and Grejner-Brzezinska, 2001a). Obviously, the image rate can be increased by using a smaller number of feature points such as a 6-10 point model, which will result in a 10 Hz rate at the coarser EO accuracy however, the robustness of the process can be impacted. Based on simulation tests, the low-level image processing tasks up to the polyline extraction seem to execute fast enough for real-time execution. The more complex image matching, however, may be a less realistic target for full real-time implementation.

4. POSITIONING ACCURACY OF THE NAVIGATION MODULE

The details of the concept of the use of real-time navigation data to support on-the-fly image processing are presented in (Toth and Grejner-Brzezinska, 2001a and b; Grejner-Brzezinska and Toth 2002). In this paper, we only present the estimated real-time navigation accuracy to support the claim that the currently implemented hardware (Litton LN100) provides sufficient short-term accuracy to enable image matching in real time. In other words, the change in position and attitude between two image captures can be estimated at the accuracy level that the image matching can be achieved at real-time. In order to demonstrate this accuracy, the reference solution based on GPS/INS data was used as a ground truth, while free navigation solution provided the actual real-time trajectory. Since two consecutive images collected at (typically) 10 Hz rate (which allows for about 1.3 m overlap), are matched using RO parameters provided by the real-time navigation solution, the primary accuracy measure for RO is the epoch-to-epoch rate of change of position and attitude error estimates. 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 fast stereo reconstruction should be feasible. The final, absolute image orientation can be performed in post-processing. Figure 5 and 6 illustrates typical differences observed between the post-processed GPS/INS and free navigation mode coordinates, and the corresponding rate of change of these differences. Figures 7 and 8 correspond to Figures 5 and 6, but illustrate the case of a sharp turn, where the navigation parameters between the two solutions can vary the most.

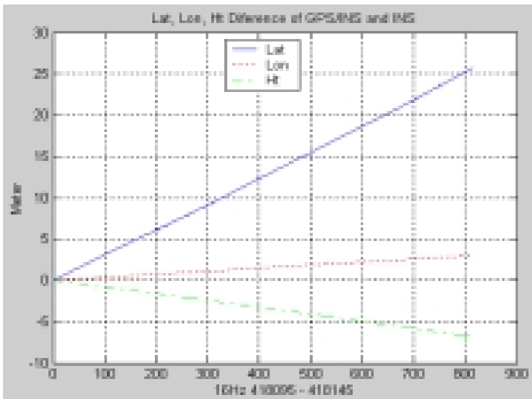

Figure 5. Difference between post-processed and free navigation coordinates.

Typically, the errors in RO range between 20 arcsec/epoch (0.01 to 0.03 m/epoch) for straight portions of the trajectory, to 60-70 arcsec/epoch (0.01 to 0.04 m/epoch) for the curves. Maximum values observed were ~200 arcsec/epoch and 0.15 m/epoch for the sharp turns. This amount of error, especially in linear offsets, may preclude real-time processing of the image pair collected at the curve (which is not really a problem from the application's point of view). In general, considering the image overlap of about 1.3 m (~50% overlap, see Table 1), the error in relative orientation of about 200 arcsec (maximum observed in our tests) will translate to an ~0.9 mm linear offset, which is practically negligible. Clearly, the error in the linear component of RO will have more impact on the image matching speed and efficiency.

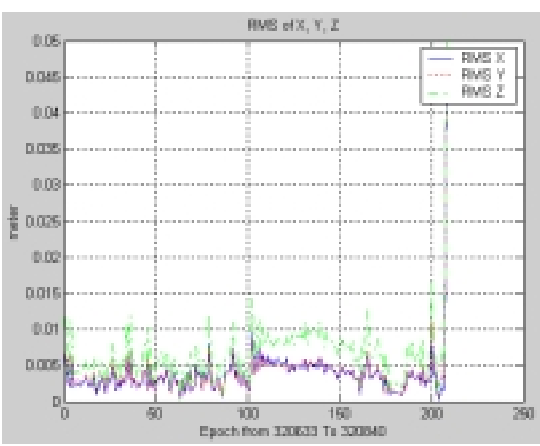

Figure 7. Estimated positioning accuracy.

As already indicated, the navigation solution estimated standard deviations are typically at the level of 2-3 cm for position coordinates, and ~10 arcsec and 10-20 arcsec for attitude and heading components, respectively, based on the variance covariance matrix, for short to medium baselines, and favorable GPS constellation and signal continuity. Figure 7 shows typical results for the positions. Naturally, the ultimate measure of the georeferencing performance is the testing of the integrated (calibrated) system, where the navigation and image components work in synch, and provide the final coordinates of the features on the ground. These, in turn, can be compared to the independently acquired ground truth. The MMS discussed here has been calibrated and tested using the ground control points surveyed by GPS and conventional surveying methods, with the accuracy of 1-2 cm in horizontal and 2-3 cm in vertical coordinates. The results of these analyses are presented in Section 6.

5. IMAGING SYSTEM CALIBRATION

The calibration of the imaging components entails two tasks: the calibration of the camera system and the establishment of its spatial relationship to the navigation system. A target area consisting of 10 main ground targets in a 10 m grid and extended with satellite points was set up at OSU West Campus to support this calibration process. Figure 8 depicts a control point with satellite points, having about 1-2 cm horizontal and 2-4 cm vertical accuracy, respectively.

5.1 Camera calibration

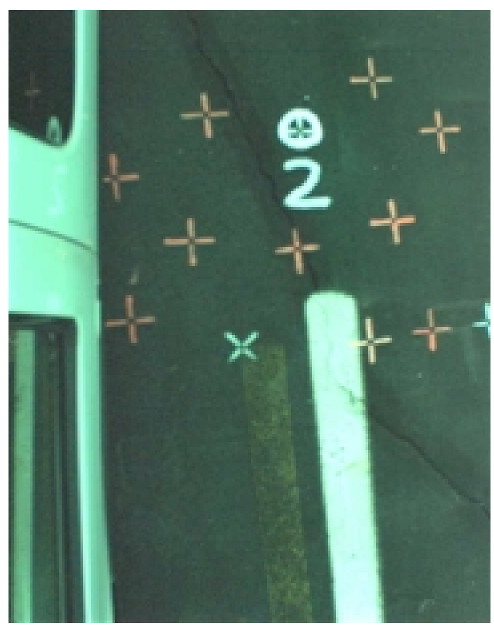

Figure 8. Calibration range target points.

For camera calibration, images were first acquired in a laboratory, using a regular grid pattern. Then image measurements of all targets from all images were obtained in a softcopy environment and subsequently processed with the OSU Bundle-Adjustment with Self-Calibration (BSC) software. Estimates of the focal length, principal point, and lens distortions were then computed. The additional parameters for decentering distortion and the affine transformation for scale differences between axes turned out to be insignificant. The radial symmetric component of the lens distortion is shown in Fig. 9. Clearly, this camera exhibits quite significant distortions towards the edges of the image sensor (on the order of 250 microns or 30 pixels). However, the extent of the radial symmetric distortion over the typical image measurement area is only about a few pixels or about one cm at ground scale. In the next step, images were acquired in a cloverleaf pattern over the ground target area by the camera installed in the mapping vehicle. Results from the triangulation with self-calibration using the AeroSys program have delivered virtually identical camera calibration parameters.

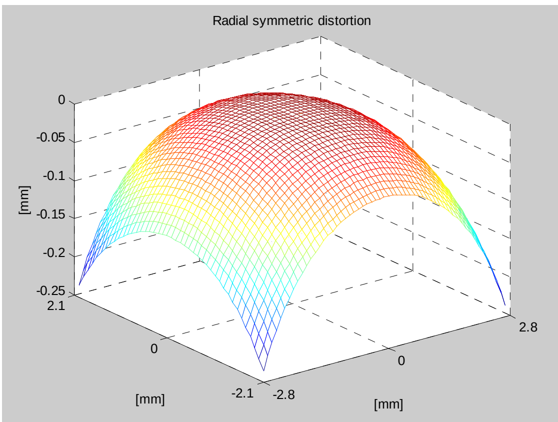

Figure 9. Radial symmetric distortion.

5.2 Boresight calibration

Boresight calibration is referred to as the estimation of the linear and angular components of the transformation between the camera and the INS body frames. It is usually accomplished through a mathematical comparison of the aerotriangulation (AT) solution and an independent GPS/INS solution for the exterior orientation parameters. The boresight calibration of the system presented here has been performed at the OSU West Campus target area after the hardware was installed in the mapping van and thereafter for stability check. The sensor configuration is shown in Figure 10; the GPS antenna is approximately above the IMU center.

Figure 10. Sensor geometry.

In each boresight calibration session, a total of three-four independent EO solutions were determined, based on several independently collected sets of three images each. The typical AT results have shown standard deviations of about 1 cm for the positions and 10 arcminutes for the attitude, respectively. The average boresight parameters are in Table 2.

Offsets in IMU body frame [m]		Rotation [degree]	
dX	-1.104	**ω**	11.160
dY	0.047	**φ**	2.169
dZ	0.439	**κ**	88.012

Table 2. Average boresight offsets and rotations.

6. PERFORMANCE ANALYSIS

6.1 A performance limit of the system

Once the boresight parameters had been established for the first time, a performance evaluation test was performed at the OSU West Campus. The objective was to test the performance potential of the system using operator based measurements. Image orientation data (EO) was provided from the GPS/INS navigation solution by applying the boresight transformation. Several models were set up and the control point coordinates (as check points) were measured in the directly oriented images and compared to the ground coordinates. Table 3 presents a sample comparison of these coordinate differences. It should be pointed out that in the analysis presented here, only the final positioning performance is addressed, which can be interpreted as the ultimate limit for the automated image sequence processing technique.

	X [m]	Y [m]	Z [m]
Point 1	-0.014	0.011	0.032
Point 2	0.015	0.045	0.060
Point 13	0.024	-0.010	0.039
Point 14	0.015	-0.045	-0.083
Mean	0.010	0.000	0.012
RMS	0.017	0.038	0.064

Table 3. Checkpoint fit to ground truth.

6.2 Realized performance

To assess the performance of the system, absolute and differential tests were performed on various roads. A few control points were set up along a centerline at the OSU West Campus and were regularly surveyed from both directions. The acquired image sequences have been processed in two different ways. In monoscopic mode, the centerlines were extracted and the location was computed from the approximation that the vehicle is always parallel to the road surface (the image ray intersects with the base plane of the vehicle). To support the stereo positing, the consecutive images were matched to establish 3D geometry and thus centerlines could be determined in the 3D space. Experiments have revealed that the matching process is not only very time-consuming but it is rather unreliable as well. To some extent, however, the monoscopic results have turned out to be quite good and rather insensitive to data acquisition anomalies, such as gaps between lane markers or missing images. Therefore, we temporarily abandoned the idea of the stereo technique and focused only on the monoscopic approach, which has definite advantages for real-time implementation. Currently, the image sequence processing rate is around 5 FPS, which is only about 50% of the maximum image capture rate. As it is already not far from a true real-time solution, and code optimizations and CPU power are also improving, the prospects are excellent. The current performance is quite satisfactory considering the processing time of the navigation solution. Figure 11a shows automatically extracted centerlines around the area where four ground control points were established (the control points are spaced at 3 m intervals), different directions are color-coded. Figure 11b shows the same area at large scale. There is clearly a visible offset between the two directions, of about 7-8 cm. This could be due to boresight error; or light conditions, such as direct sunshine or shade; or simply the limitations of the monoscopic model, such as uneven tire pressure that may change the assumed geometry. Subsequent tests have showed similar patterns. In fact, there has been a surprisingly good match for the same direction passes as the difference between the lines was usually 2-3 cm or less. Finally, Figure 14 shows a short six-lane highway segment surveyed in both directions.

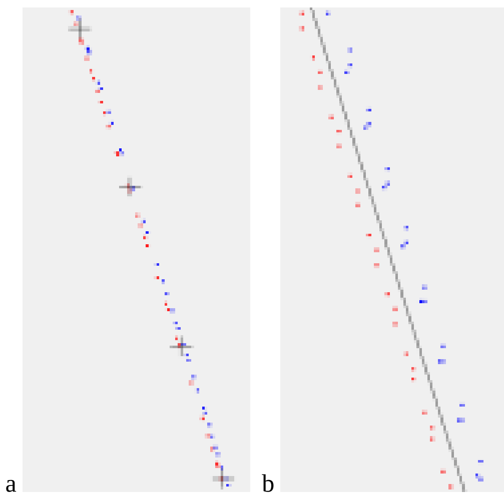

Figure 11. Automatically determined centerline positions from two passes around four control points.

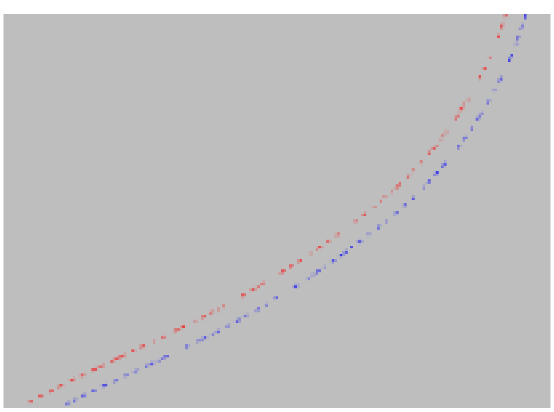

Figure 14. Six-lane highway, lane marker between the two outer lanes surveyed in both directions.

7. CONCLUSIONS

A MMS designed for mapping the center and edge lines of highways has been introduced, and its operational components were described. The positioning accuracy presented was based on actual field tests and a post-processing mode of operations. Initial results have demonstrated that a monoscopic image sequence solution can achieve positioning accuracy within about 5-10 cm in near real-time operation. The ultimate goal of the system is to process the imagery in real time. However, more software and possibly hardware optimization is needed to achieve this objective. From our experiences, it is also clear that the current hardware performance is not yet ready to support the more demanding stereo technique-based processing in real-time.

8. ACKNOWLEDGEMENTS

The authors would like to thank Eva Paska, Nora Csanyi and Ian Grender, graduate students from CEEGS OSU, for their help in test data collection and processing.

9. REFERENCES

Grejner-Brzezinska D. Mobile Mapping Technology: Ten Years Later, Part I, *Surveying and Land Information Systems.* 2001, Vol. 61, No.2, pp. 79-94 and Part II, Vol. 61, No.3: 83-100.

Grejner-Brzezinska D. A. and Toth C. Multisensor System for Automatic Monitoring of Highway Linear Features, accepted for FIG XXII International Congress Washington, D.C. USA, April 19-26 2002.

Grejner-Brzezinska D. A., Toth C. K. and Yi Y. Bridging GPS Gaps in Urban Canyons: Can ZUPT Really Help?, Proceedings, ION GPS, Salt Lake City, September 11-14, 2001, CD ROM.

Grejner-Brzezinska D. A., Yi Y. and Toth C. K. Precision GPS/INS Navigation in Urban Canyons: Dealing with GPS Losses of Lock, Proceedings, IAG 2001 Scientific Assembly, Budapest, Hungary September 2-7, CD ROM.

Grejner-Brzezinska D. and Toth C. Precision Mapping of Highway Linear Features, Geoinformation for All, Proceedings, XIXth ISPRS Congress, July 16-23 2000, Amsterdam, Netherlands CD ROM: 233-240.

Grejner-Brzezinska D. A., Da, R., Toth C. GPS Error Modeling and OTF Ambiguity Resolution for High-Accuracy GPS/INS Integrated System, *Journal of Geodesy*, 1998, 72(11): 628-638.

Toth, Ch.K., Grejner-Brzezinska, D. A., High-Precision Integrated GPS/INS/CCD System for Transportation Applications, in *Vistas for Geodesy in the New Millennium*, Eds. Adam-Schwartz, Springer Verlag, pp. 335-340, 2002.

Toth C. K. and Grejner-Brzezinska D. A. Modern Mobile Mapping: Moving Toward GPS/INS-aided Real-time Image Processing, Proceedings, ION GPS, Salt Lake City, September 11-14, 2001, CD ROM (b).

Toth C., Grejner-Brzezinska, D. A. Performance Analysis of the Airborne Integrated Mapping System (AIMS™), Proceedings, ISPRS Commission II Symposium on Data Integration: Systems and Techniques, 1998: 320-326, July 13-17, Cambridge, England.