THE UNIVERSITY OF CALGARY

DEPARTMENT OF GEOMATICS ENGINEERING

A PROPOSAL TO THE CENTRE FOR TRANSPORTATION ENGINEERING AND PLANNING (C-TEP)

TRAFFIC ACCIDENT RECONSTRUCTION USING GPS AND NON-METRIC IMAGERY

By

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INTRODUCTION

Most motorists have encountered an accident scene where police officers have delayed or diverted traffic in order to complete a site survey or map. Such site surveys are used to record the information relevant to the positions and orientations of the vehicles and passengers involved as well as any debris and skid marks and the roadway itself. This process can often require several hours of work and, therefore, cause traffic delays. Measurements consist of distances and related notes that the officers use to plot the accident scene upon return to their office. This prolonged exposure of the officers to the accident scene causes increased possibility of injury from the traffic still in the area. In some cases, the need to expedite the mapping process results in missing or incorrect data. Some of this data would be otherwise lost once the accident is cleared (Noon, 1992).

By using images for measurements, potentially lost data can be recovered. Obtaining measurements from images have been possible for some time, however it requires that the camera be calibrated. This is not the case when dealing with police cameras since they typically use amateur cameras with auto-focus or adjustable focal lengths. It is the intent of this project to produce an image-based measurement system that would be useable by police investigators.

The preliminary work outlined in this application is intended to carry out a proof-of-concept/feasibility study for the development of a system for the reconstruction of traffic accident scenes from non-metric imagery. The applicant intent to secure additional funds for longer term funding from the City of Calgary, Engineering Services and/or industry partner.

PROPOSED METHODOLOGY

The proposed system will exploit existing digital map files and receivers of the Global Positioning System (GPS) for the generation of control information. This control information comes in the form of three-dimensional coordinates (X, Y and Z) and these coordinates define a reference frame that is valid throughout a municipality (Karimi and Chapman, 1997). Typically, a municipal Geographic Information System (GIS) will contain digital map data of all of the street and utility networks (such as signage, hydrography, residences, businesses and utility poles). Much of the information destined for a GIS is visible from the street networks. Consequently, these digitized features will be visible in much of the imagery (digitized photography) captured at accident scenes within the city limits. In the case of areas outside of the city or with missing data, alternative control can be supplied with the receivers of the GPS system.

The proposed process involves the development of algorithms and software for the simultaneous calibration (interior orientation) and exterior orientation of imager (in this digital color camera). Camera calibration involves the mathematical recovery of such parameters as the focal length, principal point (where the optical axis intersects the image plane) and lens distortion parameters. The process of exterior orientation re-establishes the precise position and attitude (orientation) of the camera with respect to a defined reference frame. Normally, the coordinates derived from the digital map file would define this reference frame. The challenge in this project is to achieve accurate results using imagery acquired from cameras with auto-focus or variable focal length settings.

In order to begin the project, algorithms that will model the internal geometry of non-metric imagery must be developed. Non-metric imagery generally refers to imagery that is acquired from cameras with unstable interior orientation (or geometry) due to auto-focus or variable focal length capabilities. Previous experiences of one of the researchers have shown that such algorithms are achievable and that camera calibration is possible when proper procedures are followed. Upon development and implementation of these algorithms, the police images will be displayed on a computer monitor. A software package that permits the measurement of features of interest will be developed in parallel with the calibration software.

At the same time, a software package will be produced for the purpose of extracting three-dimensional information from existing digital map files or through the use of GPS measurements (Chaplin et al, 1997). These derived coordinates are then used to define a reference frame upon which the camera calibrations and exterior orientations can be computed. This software must interact with the image measurement software so that both image coordinates (x,y) and ground coordinates (X, Y and Z) can be captured for conjugate points. When multiple images "see" the same point then constraints can be imposed to ensure that the image rays intersect at the same position in object space (i.e., the real world). These intersection constraints along with the three-dimensional coordinates constraints permit the recovery of both the interior and exterior orientations (Baltsavias, 1991). Once these orientations are established, then image measurements to any other point of interest can be made on multiple images. The corresponding three-dimensional coordinates of this point can be computed using intersection equations. A map of an accident scene can then be created using all of the three-dimensional information coming from the digital maps, GPS or as computed thorough the intersection equations.

RESEARCH STRATEGY

As mentioned above, this research work was aimed at developing a system for the generation of maps of traffic accident scenes using police imagery. A proof-of-concept is proposed involving the development of a prototype acquisition system and software modules to assess the feasibility and performance of the system prior to the full-scale implementation. The specific research objectives are as follows:

1. System Simulation

The process of simulation involves the generation of camera model algorithms and idealized data sets. These data sets will be used to test the performance of the mathematical models in terms of accuracy and reliability. With the introduction of realistic random errors, the processing algorithms are then subjected to a rigorous evaluation. This phase of the project will take three weeks to complete since it involves the implementation of many algorithms previously developed by the applicant's research group.

2. Data Processing Algorithms

Through number of other imaging research projects, experience has been gained in the development of camera calibration models for non-metric and digital cameras (El-Sheimy, 1999). The mathematical models will be designed to represent the geometric processes of the imaging system including distortion or error sources. These error sources include incorrect focal length value, principal point offsets and lens distortion. In the case of digital cameras or scanned imagery, then there are additional errors that cause differential scales and affinities (skewness). A model that simultaneously estimates the camera calibration parameters and the exterior orientation elements will be used. Normally, the control used for such calibrations has and accuracy of less than a centimeter. The novel aspect of the project is based on the use of control from digital map files and GPS which have three dimensional accuracies of 10-15 cm. Such poorer control information will compensated by the use of intersection constraints which supply excellent relative accuracies. By introducing a scale constraint into the imagery (e.g., a measured distance), the resulting three-dimensional coordinates will be adequate for the needs of the police (e.g., 1-2 cm).

The majority of the time in this phase of the project will be spent on the software implementation of the algorithms and the refinement of the mathematical models and statistical weighting schemes.

3. Integrated Image Measurement and Digital Map File Processing

This phase of the project will focus on the development of an image measurement and digital map file processing software package. The image measurement aspect involves the production of an image display and point measurement software package. The user will have the capability of measuring points of interest such as control points as well as other important features recorded in the imagery. These features could include points on the vehicles, skid mark start and end position, debris and roadway elements such as signs and curbs. A beta-version of the image measurement software package has been under development for metric cameras, by one the of the applicant's graduate students (under one of the UofC URGC projects, Start date: October, 1999). See Figure 1 for the general layout of the current version of the image measurements software.

The second task in this phase involves the development of a software package for digital map file processing. This package will permit the user to extract three-dimensional coordinates of control points to be used in the camera calibration and exterior orientation phases. To ensure optimal data collection, this package will be integrated with the image measurement module so that corresponding image and object (i.e., real-world) point coordinates can be reliably collected.

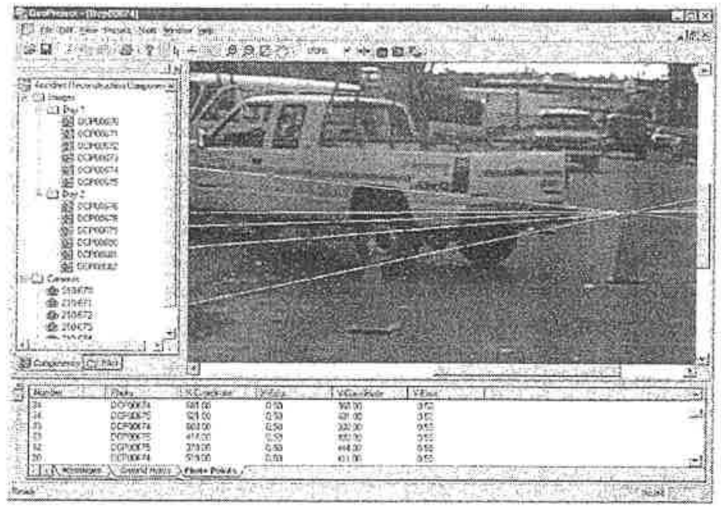


Figure 1: The Image Measurement Software

The image measurement module will be completely developed first then followed by the digital map file processing module. This development sequence would allow the image measurement software to be available for generating image coordinates for testing the camera calibration and exterior orientation routines. The same graduate student would subsequently complete the digital map file processing routines. This development continuity would ensure optimal integration of this routine with the image measurement module.

4. Prototype Testing

Different image sequence will be tested in order to assess the effectiveness of the developed system and procedures. Initially testing will be carried out on a stereo pair basis using control points established in the field. The objectives will be to achieve sufficient point estimation accuracy using the GPS, the georeferenced data, and image measurements. Enhancement to the point measurement software tools will be implemented during this phase. Previous experience has shown that the automation of the image enhancement represents a formidable task. It is anticipated that the three-dimensional coordinates derived from the developed system will have an accuracy of 5-10 cm. The operational testing will take place during the last month of the project.

SYSTEM CONCEPT

Figure 1 shows a schematic diagram of the prototype model of the PMM system. The system integrates a NovAtel OEM3 dual-frequency GPS receiver with a Leica Digital Magnetic Compass (DMC) system and a Kodak DC260 digital camera.

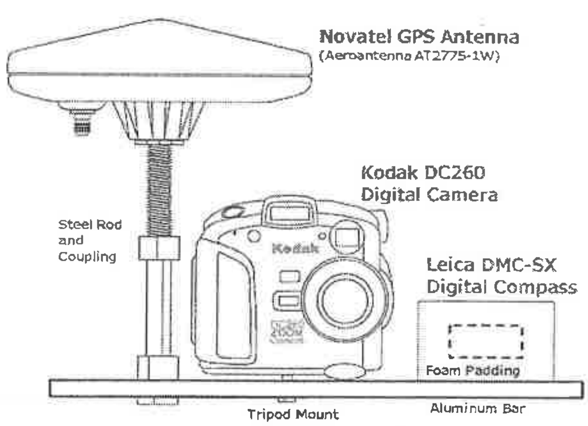


Figure 1: Schematic of the PMM System

The GPS is the positioning sensor for the PMM system. The selection of a dual-frequency receiver would appear run contrary to the design goal of a less-expensive system. However, the relatively poor accuracy of the orientation sensors in the PMM system means that the GPS positions are important for controlling the orientation of the photogrammetric networks measured from the images taken by the system (Ellum and El-Sheimy, 2002).

The Leica DMC is the orientation sensor for the PMM system. The DMC is a solid-state sensor module that provides the full three-dimensional attitude angles: azimuth, roll and pitch. The DMC, shown in Figure 2, is small in size, has low power consumption, and is lightweight. All of these characteristics make it well suited for inclusion in the PMM system. The trade-off for these features is a lower accuracy – roll and pitch are only accurate to approximately 0.5°, and azimuth is accurate to about 1°.

The Leica DMC consists of three micro-electromechanical (MEMS) based accelerometers and three magnetic field sensors. The DMC, like all magnetic sensors, determine the azimuth by sensing the components of the Earth's magnetic field through its three magnetic files sensors. Similarly, the accelerometers sense the direction of the gravity vector from which the roll and pitch angles can be easily calculated. However, local disturbances in the field caused by nearby permanent magnets, electric currents, or large iron bodies can dramatically affect the derived azimuth. As a consequence of this phenomenon, the determined azimuth bias changes more in relation to location than with the time elapsed since the last update. Because the earth's magnetic field is the reference, the azimuth angles from the DMC must be corrected for magnetic declination if they are to refer to true north. Fortunately, there are freely available global models of the Earth's magnetic field. These models provide all three components of the Earth's magnetic field for certain date, longitude, latitude and elevation. These models compute the estimated values of the Earth's magnetic field, including magnetic declination, based on the current International Geomagnetic Reference Field (IGRF) (NIMA, 2000). While results are typically accurate to 30 minutes of arc, solar storms could cause intense short-term disturbances in the magnetic field.

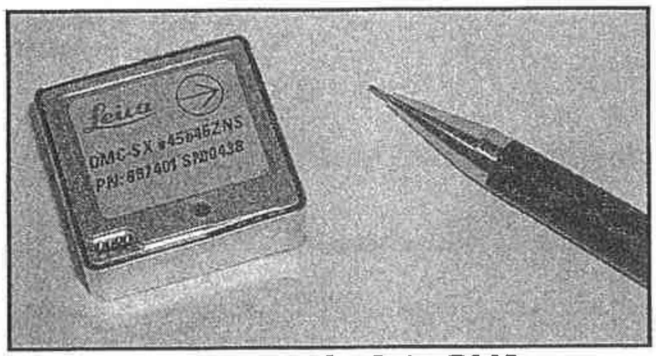


Figure 2: The Leica DMC

The accuracy of DMC derived azimuth depends heavily on the degree to which the local magnetic field is being disturbed. Disturbances in the magnetic field can be divided into two categories: hard-iron and soft-iron. Hard-iron effects, or local fields, can be modeled as static fields such as those created by permanent magnets. Hard-iron distortions are significant in most systems. Soft-iron effects are created by the amplification of magnetic fields by highly permeable materials, such as ferrous metals. The DMC implements several internal calibration routines that perform both hard-iron and soft-iron calibrations. For a review of hard-iron and soft-iron disturbances, see Caruso (2000) and for more details about calibration of magnetic sensors, see Gebre-Egziabher et al. (2001).

The digital camera used in the prototype model is the Kodak DC260. Consumer digital cameras are ideal for inclusion in portable mobile mapping systems because of their large color image format, low cost, and large internal memory. The internal memory of the camera is particularly valuable because it negates the requirement to transfer the images to a logging computer.

As outlined above, the primary components of the system are a GPS receiver, an attitude sensor, and a digital camera. Additionally, a logging computer is required to store the measurements and – if the system is implemented in real-time – to do the processing. These components are connected as shown in Figure 3. In this arrangement, the GPS receiver is the core of the system, and is responsible for both making its own measurements, and for time-tagging the DMC's measurements and the images exposure times. It would also be possible to have both the GPS and the DMC connected to a computer; however, this would require either complex software timing or an expensive timing board. Passing the DMC's measurements and the camera signal of the exposure instant through the GPS eliminates these requirements.

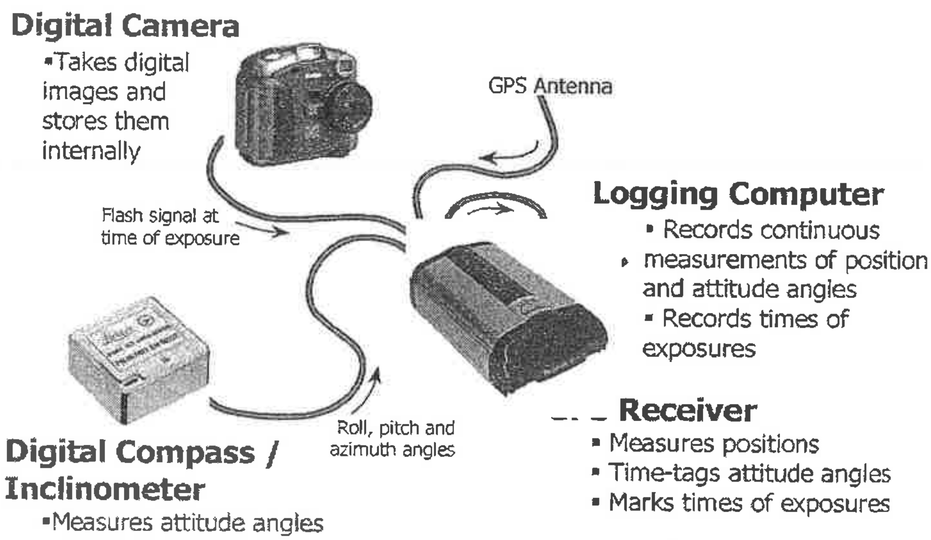


FIGURE 3: HARDWARE INTEGRATION OF THE PMM SYSTEM

GEOREFERENCING AND 3D COORDINATE COMPUTATION

Georeferencing is the process of estimating the position and orientation of an imaging sensor in a multi-sensor system. In van-based MMS that integrate GPS with INS both the position and orientation can be measured directly from the navigation sensors. These estimates can then be used with image point measurements to calculate the co-ordinates of points and features visible in the images. This process, shown in Figure 4, is referred to as direct georeferencing. More details of this technique are available in Schwarz et al. (1993). Unfortunately, the lower orientation accuracy of the DMC, used in the PMM system, means that direct georeferencing is not possible. Instead, a photogrammetric bundle adjustment must be used that takes advantage of the additional orientation information provided by the GPS positions. This technique is referred to as indirect georeferencing.

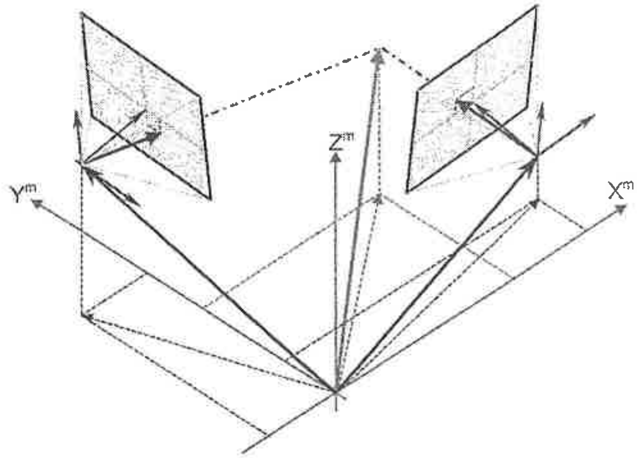


Figure 4: Direct Georeferencing

The basis of the georeferencing process – be it direct or indirect – is a 7-parameter conformal transformation in which the co-ordinates of a point in the camera coordinate frame (c-frame) are related to its coordinates in a mapping co-ordinate frame (m-frame). Expressly, this relation is given by:

$$\mathbf{r}_P^m = \mathbf{r}_c^m + \mu_c^m \cdot \mathbf{R}_c^m \cdot \mathbf{r}_p^c \qquad (1)$$

where,

$\mathbf{r}_p^m$ is the co-ordinates of a point (p) in the m-frame,

$\mathbf{r}_c^m$ is the position of the camera in the m-frame,

μ_c^m is the scale factor between the c-frame and the m-frame,

$\mathbf{R}_c^m$ is the rotation matrix between the c-frame and the m-frame, and

$\mathbf{r}_c^m$ is the co-ordinates of the point (p) in the c-frame.

In the PMM system, both $\mathbf{r}_c^m$ and $\mathbf{R}_c^m$ are measured – albeit indirectly. In reality, GPS provides the position of the antenna in the mapping co-ordinate frame. Consequently, to relate the camera and the GPS the offset vector between the two sensors is required. If this offset vector is measured in the camera frame, then the relation is given by:

$$\mathbf{r}_c^m = \mathbf{r}_{GPS}^m + \mathbf{R}_c^m \cdot \mathbf{r}_{GPS}^c \qquad (2)$$

where

$\mathbf{r}_{GPS}^m$ is the co-ordinates of the GPS antenna in the m-frame, and

$\mathbf{r}_{GPS}^c$ is the co-ordinates of the GPS antenna in the c-frame (i.e., the offset vector).

The DMC measurements are used in a similar fashion to the GPS measurements. The DMC provides attitude angles (roll, pitch, and azimuth) that relate its axes to the axes of the m-frame. These angles can be used to construct the rotation matrix $\mathbf{R}_{DMC}^m$. To estimate the rotation matrix $\mathbf{R}_c^m$, used in Equation (1), an additional rotation matrix, $\mathbf{R}_c^{DMC}$ is required that relates the c-frame with the DMC-frame. If this is available, then $\mathbf{R}_c^m$ can be obtained using:

$$\mathbf{R}_c^m = \mathbf{R}_{DMC}^m \mathbf{R}_c^{DMC} \qquad (3)$$

Substituting Equations (2) and (3) into Equation (1) yields the complete georeferencing formula for the PMM. Explicitly, this is:

$$\begin{aligned}\mathbf{r}_p^m &= \mathbf{r}_{GPS}^m - \mathbf{R}_{DMC}^m \mathbf{R}_c^{DMC} \mathbf{r}_{GPS}^c \\ &\quad + \mu \mathbf{R}_{DMC}^m \mathbf{R}_c^{DMC} \mathbf{r}_p^c\end{aligned} \qquad (4)$$

This relationship is shown below in Figure 5.

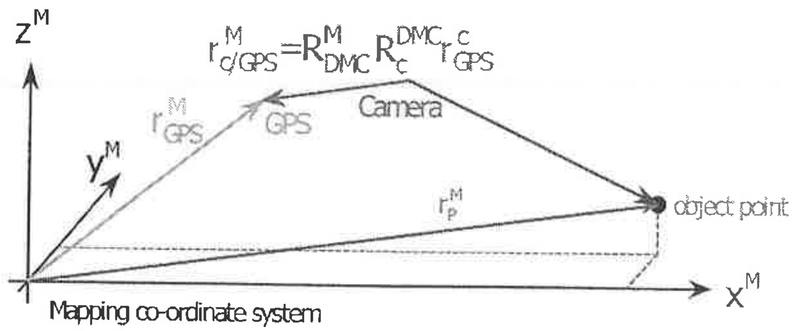


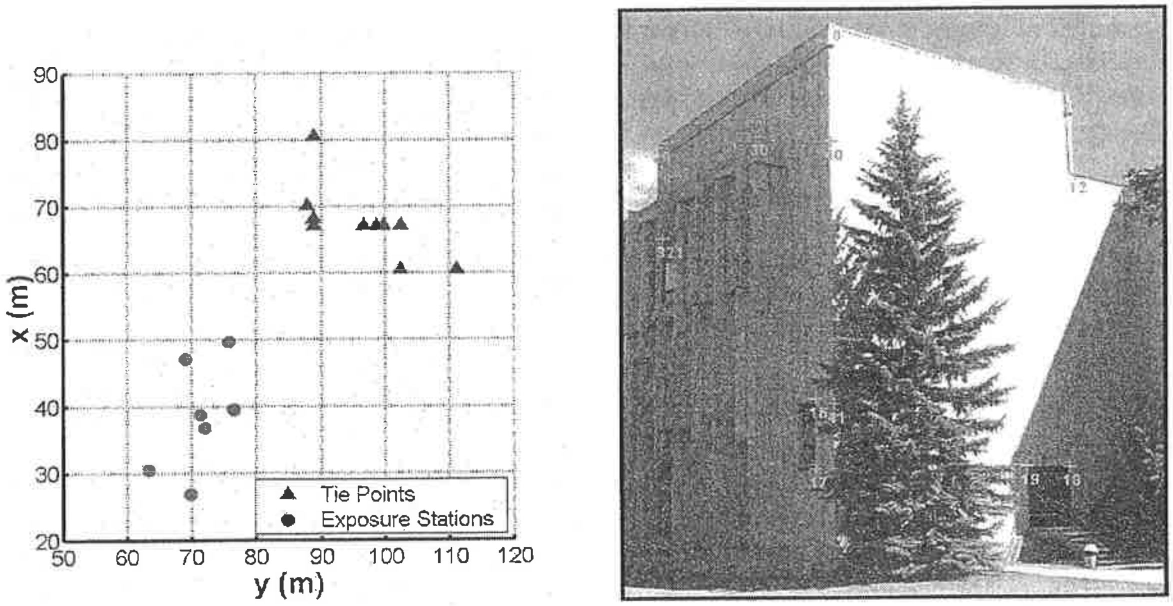
Figure 5: Sensor relationship in PMM

To perform a photogrammetric bundle adjustment, Equation (1) is solved for the image point measurements and the third equation in the system of equations is algebraically eliminated. The resulting observation equations, which are essentially modified collinearity equations, are then used in a photogrammetric bundle adjustment. In addition, the position and orientation estimates provided by the GPS and DMC are included as weighted parameter estimates in the adjustment (Mikhail et al., 2001). The physical interpretation of this is that the GPS positions are fixing the scale, translation, and – depending on their number – one or more of the datum rotations and the DMC angles are fixing the rotations of the datum.

SYSTEM TESTING AND RESULTS

The main objective of the PMM system is the 3-D coordinate determination of points or features within the field of view of the digital camera. The accuracy of the coordinates is a function of the complete processing chain, which involves GPS positioning, DMC attitude determination, target localization in the images, system calibration, distance between the object and the cameras, and the camera geometry used in the 3-D computation. To test the developed prototype system, a target field of ground control points (GCPs) was established that simulated a "typical" urban environment in which the PMM system would be expected to operate. The target field had nearby vertical structures, pavement, and foliage - in short, somewhat of a worst-case environment for GPS. It also had nearby metal buildings and light standards that could influence the azimuth reported by the attitude sensors. This field was approximately 30 meters wide and 10 meters in depth, shown in Figure 6, and the images for the tests were taken at object to camera distances of approximately 25 m from the target field. The azimuths from the DMC have first been corrected for magnetic declination using the Geological Survey of Canada's Magnetic Information Retrieval Program (MIRP) (GSC, 2000).

The target field was initially surveyed and adjusted using GPS baselines, EDM distances, and horizontal & vertical angles. However, to further increase the accuracy of the surveyed points, and to most accurately determine the exterior orientations of the test images, the measurements from all the images used in the tests were also included in an combined photogrammetric/terrestrial adjustment. Additionally, the interior orientation and lens distortion parameters of the camera were calibrated simultaneously, although results from a previous calibration were included as weighted parameters. The reported standard deviations for the object space co-ordinates of the target points were approximately a centimeter, and these positions are treated as the "true" quantities in the comparisons in the following sections. The residual error that remains was neglected, as its relative magnitude was below the centimeter level that the results were compared at. The initial terrestrial network adjustment, the combined adjustment, and the individual photogrammetric adjustments done for the tests were all performed using the Bundle adjustment software package developed at the University of Calgary (Ellum and El-Sheimy, 2001).



(a) Planimetric View **(b) Photo**

FIGURE 6: TEST POINTS AND TARGET FIELD

Absolute Accuracy

The primary goal of the PMM system testing was to determine the achievable mapping accuracies of the integrated system. The accuracies of points in the target field measured using the PMM system are examined at different camera-to-object point distances using different numbers of images and different numbers of image point measurements.

Table 1 shows the absolute accuracy of the PMM system when three images, taken at an average distance of 25-30 m, are used. The results indicate that RMS of 0.12 m ($=\sqrt{(0.07)^2+(0.1)^2}$) in the horizontal coordinates and of 0.04 m in height can be achieved at such distances. These results have been computed using 12 checkpoints from the target field that appear in the three images. Since the errors in the target field co-ordinates are also contained in these values, it should be expected that the RMS values for the PMM system are about 10 cm for the horizontal positioning error and 4 cm for the height error.

TABLE (1): ABSOLUTE ACCURACY OF THE PMM SYSTEM

	Easting (m)	Northing (m)	Height (m)
RMSE (m)	0.07	0.10	0.04
Mean (m)	0.01	-0.08	-0.03
σ (m)	0.07	0.06	0.03

CONCLUSIONS

A Prototype model of the PMM system has been developed and tested under control environment. Major focuses of the last 8 months were in the analysis of recent field tests designed to estimate the system's absolute and relative accuracy under different operational environment. System testing results have shown that the PMM system constructed from off-the-shelf hardware can have absolute object space accuracies comparable to current standard surveying techniques used in traffic accident investigation. The analysis of the system's absolute accuracy was based on a comparison with "ground truth" that was independently determined with an accuracy of 1 cm. When using three images at a 25-30 m object-to-camera distance, agreement with pre-surveyed ground truth was generally better than 10 cm and had an RMS value of 12 cm in the horizontal coordinates and 4 cm in height. In general, the results of system testing show that the system accuracy surpasses the development objectives for the prototype system. There is considerable room for improvements that will be investigated in the next phase. We also intend to test the system later this year over a controlled accident with the City Police.

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