THE DEVELOPMENT OF A BACKPACK MOBILE MAPPING SYSTEM

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ABSTRACT

A low-cost backpack mobile mapping system is being developed in the department of Geomatics Engineering at the University of Calgary. The system will overcome the drawbacks of current mobile mapping systems – namely their high cost, large size, and complexity – which have restricted their widespread adoption in the survey industry. The development of such a system will satisfy the demand for a mobile mapping system that can compete both cost-wise and in user friendliness with current GPS and conventional terrestrial survey systems, while realising significant gains in efficiency. Also being developed concurrently with the portable mobile mapping system is photogrammetric software that can be used in computing three-dimensional mapping co-ordinates of objects visible in the captured images, and exports them to a GIS. The paper outlines the benefits of a backpack MMS, reviews the technologies available for such a system, and then discusses results from simulations using a variety of navigation sensor configurations.

1 INTRODUCTION

There is an increasing demand in both government and private industry for spatial data. This demand, which is partly fuelled by the extensive adoption of Geographic Information Systems (GIS), is, unfortunately, not well served by traditional survey and mapping techniques. Traditional techniques – including GPS – are costly and time consuming. Consequently, they act as a hindrance in many projects requiring spatial data and for the same reasons, they are also not well suited for frequent updating. In an effort to overcome the drawbacks of traditional spatial data collection techniques, there has been much research into the creation of *mobile mapping systems* (MMS). MMS combine positioning and navigation technologies with remote sensing, and are successful in overcoming many of the disadvantages of traditional surveying techniques. For a detailed examination of mobile mapping systems, see Li, 1997 or El-Sheimy, 1999. The advantages of MMS are numerous, but their key benefits are:

- The time and cost of field surveys are reduced
- Both spatial and attribute information can be determined from the remotely sensed data
- Data can be archived and revisited – permitting additional data collection without additional field campaigns

Despite these advantages, current mobile mapping systems have not gained widespread acceptance. The reason for this is clear – their complexity and high development costs severely limits their use to specific users. Cost is particularly limiting – the initial investment in such systems is too high for most survey and mapping firms, especially if the system is not operated daily. Consequently, most survey and mapping firms continue to use traditional survey techniques for their GIS data collection projects. The goal of the development of a backpack mobile mapping system is to overcome the drawbacks of current mobile mapping systems that are limiting their widespread acceptance – in short, to bring mobile mapping to the masses. The applications of a backpack mobile mapping system are numerous. They include pipeline right-of-way mapping, urban GIS data acquisition, accident reconstruction, highway inventory, facility mapping, and small-scale topographic mapping. Through the use of precise post-mission GPS ephemeris, the system could also be used in single point positioning mode for GIS data acquisition in areas without existing control.

The primary components of any mobile mapping system (MMS) are the navigation sensor(s), the mapping sensor(s), and the processing and logging computer(s). In an airborne or land-based MMS the emphasis is typically on sensors which can deliver high accuracy and high data rate. Consequently, a typical sensor configuration would be a dual-frequency GPS and a navigation-grade inertial navigation system for the navigation sensors, and a megapixel digital camera as the mapping sensor. In a backpack MMS, however, the emphasis is on small size, low cost, low weight, and low power consumption. Accuracy of the both the navigation and mapping sensors can be sacrificed in favour of these factors. However, much of this decrease in the accuracy of the sensors is compensated for by the increased mobility a backpack MMS affords a user – object to camera distances would typically be much smaller, and it is much easier to position the exposure stations to take advantage of the best possible geometry.

This paper will provide a brief review of the available georeferencing technologies suitable for a backpack mobile mapping system, and the predicted accuracy with different sensor configurations. Throughout this paper it is assumed that the mapping sensor is a low-cost consumer digital camera. It is shown in Li (1999) that with accurate calibration and at the object to camera distances that a backpack MMS will be used at, mm level accuracies in the determination of object space co-ordinates are possible regardless of the choice digital camera. Similar tests at the University of Calgary have confirmed this, and therefore the specific choice of digital camera is not critical. The development of a backpack mobile mapping system is a continuation of MMS research and development at the University of Calgary which has focused on airborne (Schwarz et al. 1994; Mostafa and Schwarz, 1999) and van mounted MMS systems (El-Sheimy, 1996).

2 GEOREFERENCING SENSORS

For an image to be completely georeferenced, the six exterior orientation parameters must be determined. These are the three components of the camera centre position vector, and the three components of the camera rotation. There are few sensor systems that can provide all six of these parameters – at least not with acceptable reliability and accuracy. Therefore, the sensors are typically divided into two categories: positioning sensors, and sensors that can be used to determine the attitude angles. A review of such sensors appropriate for a backpack MMS is presented below. In all cases, the estimates of accuracy are slightly pessimistic. This is in acknowledgement to the fact that the backpack MMS will frequently be used in less-than-ideal environments, and that manufacturer's accuracy estimates usually assume ideal or near-ideal conditions.

2.1 Positioning Sensors

GPS is the obvious choice to provide the position of the backpack MMS – indeed, the development of GPS is perhaps the primary motivator for the development of mobile mapping systems of any type (Li, 1997). Its application to other mobile mapping systems has already been proven in both aircraft mounted systems (Schwarz et al., 1994; Mostafa and Schwarz, 1999) and vehicle mounted systems (Bossler and Novak, 1993; El-Sheimy, 1996). The reason for its invariable inclusion in mobile mapping systems is that there is simply no other positioning technology that offers the same accuracy and flexibility at the same cost. With regards to a backpack mobile mapping system, GPS has a number of additional advantages. Foremost among these is that GPS already has wide acceptance in the surveying and mapping industry – the intended markets for the backpack MMS. Typical survey firms are much more likely to invest in new equipment if they already have a familiarity with the technologies that it implements. Additionally, training time for users of the backpack MMS will be reduced. GPS is not, however, perfect. Typical operating environments for the backpack MMS will include forested and urban areas. In both environments GPS is subject to satellite masking and multipath that reduces its availability and reliability. Originally, it was planned to use a low-cost Inertial Measurement Unit (IMU) to provide position during periods of GPS signal outages. However, preliminary investigations into such a system – the Crossbow DMU-FOG – at the University of Calgary have demonstrated that they cannot deliver the required positioning accuracy.

GPS can be operated in a variety of modes. The modes that are potentially applicable to a backpack MMS and their associated accuracies are listed in Table 1. All values quoted assume a ten-kilometre baseline. A significant difference between GPS receivers not shown in the table is their price. Single frequency (L1 only) GPS receivers typically cost approximately $5000 US – although single frequency receivers are available for as low as several hundred dollars. Unfortunately, cost and performance in GPS receivers can be highly correlated, and therefore the use of lower price receivers may not be advisable if the system is not to be plagued by low reliability. Dual frequency (L1/L2) receivers cost considerably more than single frequency receivers – typical prices are between $10 000 US and $25 000. This significant increase in price will undoubtedly preclude their use in a low cost backpack MMS, despite their much-improved real-time Kinematic (RTK) performance.

GPS Type	Position Accuracy	
	Horizontal (2DRMS)	*Vertical (RMS)*
Code Differential (Narrow Correlator, Carrier-phase smoothing)	0.75 m	1.0 m
L1 Carrier-phase RTK (Float ambiguities)	0.18 m	0.25 m
L1/L2 Carrier-phase RTK	0.03 m	0.05 m
L1 and L1/L2 Post-mission Kinematic	0.02 m	0.03 m
L1 Precise ephemeris (with Ionospheric Modelling)	1.0 m	3.0 m

Source: Manufacturer's Product Literature, Schwarz and El-Sheimy 1999, Lachapelle et al., 1994

Table 1: Accuracy of GPS

2.2 Attitude Sensors

The selection of attitude sensors is more difficult than the selection of the positioning sensor – GPS in this case. The reason for this is that pace of development in attitude sensing technologies is not at the level of GPS development, and therefore the comparative accuracy-for-price is not available. Also, several sensors – or combination of sensors – exist that provide essentially the same accuracy. Fortunately, at the object to camera distances that the backpack MMS will be used for, the attitude accuracy is not as critical as position accuracy. A list of possible sensors for attitude determination is shown in Table 2. The accuracies stated are for tilt angles (roll and pitch) below 20°.

Sensor Type	Attitude Angle Accuracy *Roll and Pitch*	 *Azimuth*	Cost (USD)
Six-Axis Tactical Grade IMU	0.25°	2°	$12000 - $20000
Twin Antenna GPS	1.0° (One Angle Only)	0.75°	$2000 - $6000
High-Accuracy Tilt Sensor	0.05°	–	$3500
Low-Accuracy Tilt Sensor	0.25°	–	$700
Magnetic Azimuth Sensors	–	1.0°	$250
3-Axis Magnetometer Integrated with 2-Axis Tilt Sensor	0.25°	1.0°	$700 - $1200

Source: Manufacturer's Product Literature; Schwarz and El-Sheimy 1999; Szarmes et al., 1997

Table 2: Sensors for Determing Attitude

As noted previously, it was originally intended to use a low-cost strapdown IMU as part of the backpack MMS, and such an IMU – the DMU-FOG – was acquired from Crossbow Technology for testing purposes. This IMU – available in single units at approximately $8000 US – uses Micro-Electro-Mechanical Systems (MEMS) accelerometers to measure acceleration and Fiber-Optic based gyros (FOG) to measure angular rates. However, preliminary investigation has shown that this DMU has a high gyro drift rate, as shown in Figure 1. This high drift will not allow accurate azimuth determination without the use of additional heading sensors or the implementation of special processing techniques (such as azimuth updates from GPS derived positions). The second option is currently under investigation. An alternative to a low-cost IMU is a more accurate tactical-grade IMU, as shown above in Table 2. However, for integration in a low-cost system, a tactical grade IMU is handicapped by its high cost, weight, and power consumption. Despite these drawbacks a tactical grade IMU is still attractive because of its well-known error characteristics and its ability to bridge GPS signal outages. Also, integrating an IMU would allow the backpack MMS to be used on dynamic platforms.

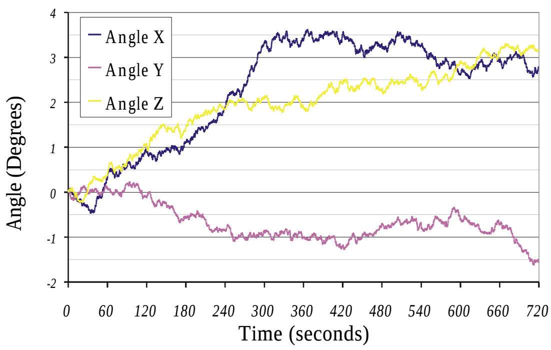

Figure 1: Angular Drift from Low-cost Strapdown IMU (Crossbow DMU-FOG)

Recently, there has been much research conducted on attitude determination using GPS multi-antenna systems. The accuracy of attitude angles determined by GPS is a function of the baseline distance between the antennas. Obviously, if the backpack MMS is to be considered portable than a large separation between antennas is not feasible. Fortunately, tests at the University of Calgary have confirmed 0.75° accuracies are possible over half-meter baselines (Szarmes et al., 1997). However, these tests have also shown some of the drawbacks of attitude angles determined by GPS – namely, their sensitivity to satellite masking and shading. This effects both the accuracy and reliability of the results. A three-antenna GPS system would provide all three attitude angles and a degree of redundancy. However, to achieve sufficient accuracy over short baselines such a system would require the antennas to be mounted in a triangular configuration. This configuration would be too unwieldy for a backpack MMS and therefore only a two-antenna system is feasible. Unfortunately, such a system only provides two of the three attitude angles. It is also worth noting that it is not possible to interpolate between the GPS positions to determine azimuth as the backpack mobile-mapping system is not a rigid body, and the direction of the camera's axis will not, in general, be parallel with the direction of travel.

Low-cost tilt sensors (also called inclinometers) are another option for providing some of the attitude parameters for the backpack MMS. These sensors use either liquid filled electrolytic tilt sensors, or MEMS based accelerometers. In either case, the sensor determines the roll and pitch angles by detecting the effect of earth's gravity on the sensing system. Not surprisingly, the accuracy of tilt sensors is proportional to their price. Advertised accuracies of low-cost tilt sensors are between 0.2° and 0.5°, while higher cost systems claim to provide accuracies of approximately 0.2% of the actual reading (Clino Ltd., 2000). The accuracy of tilt sensors is also proportional to the degree of tilt – as tilt angle increases, accuracy degrades. However, the backpack mobile mapping system would not typically exceed tilt angles of 20°, and within this range tilt angle accuracy is reasonably stable. A potential drawback to the use of tilt sensors is that they require as much as several seconds settling time in order to produce an accurate output. During this period the sensor must not move. However, in the static applications that the backpack MMS would be used this figure would not be a serious drawback, as practically speaking the system would have to be held motionless for several seconds anyway to capture the images. A final advantage of tilt sensors is that their power consumption is very low – typical values are less than 0.3 W.

Magnetic sensors are the lowest cost method for azimuth determination. Basically they are the strapdown equivalent of a compass. Their accuracy is dependent on many factors, including temperature, sensor tilt, and the presence of nearby ferrous material. The former two effects can be modelled or calibrated. The latter effect, however, is a potential drawback of such sensors, as one of the environments that the backpack MMS will be used is in urban areas where there are large magnetic and electrical fields. The effect of these fields on the accuracy of the sensor, and techniques to mitigate their effect, must be investigated. Magnetic sensors also require knowledge of the earth's magnetic field, as magnetic north does not coincide with geodetic north. However, highly accurate global and regional models of the earth's magnetic field are freely available from a wide variety of sources. Like tilt sensors, magnetic sensors also have very low power requirements – typical values are under 0.2 W.

Of the systems described above for determining the camera orientation, only the IMU can provide all three attitude angles. Therefore, for the other systems to provide all three attitude angles they must be combined with additional sensors. One possibility is to combine a magnetic sensor with a two-axis tilt sensor. Such a system provides all three attitude angles, is small in size and weight, and has low-power requirements. It is listed in the table above because such systems are available "off-the-shelf" – examples include the Honeywell HMR3000 or Precision Navigation's TCM2. Other examples of sensor combinations for attitude determination include a dual-antenna GPS with a tilt sensor. Such a system has the advantage of redundancy in the calculation of tilt angles. The existence of a redundant solution would improve accuracy, and also help in determining blunders in the GPS derived azimuth – a problem in non-ideal environments in which the system will operate.

3 3-D FEATURE EXTRACTION

Once the images have been georeferenced and the position and orientation of the camera perspective centres are known, determining the 3-D co-ordinates of any feature visible in the image is a straightforward intersection in space. After correcting for principal point offset, radial lens distortion, and decentering lens distortion the functional relationship between the image co-ordinates vector $\mathbf{r}^{c}$ and the mapping frame co-ordinate vector $\mathbf{r}_{P}^{M}$ is given by:

$$\mathbf{r}_{P}^{M} = \mathbf{r}_{c}^{M} + l\,\mathbf{R}_{x}(\omega)\mathbf{R}_{y}(\varphi)\mathbf{R}_{z}(\kappa)\mathbf{r}^{c}$$

In the above equation, $\mathbf{r}_{c}^{M}$ and ω, φ, and κ are the position vector and attitude angles of the camera centre at time of exposure respectively, and l is the scale factor between image and object space. Figure 1 shows in schematic form the relation between different elements of the above equation (for clarity, airborne image geometry is used – however, the principle is the same regardless of the imaging geometry). To determine the mapping-frame co-ordinates of features visible in the images, the above equation is first linearised and then least squares is used to solve for the unknown parameters – the three mapping frame co-ordinate unknowns, and an unknown scale factor for each image introduced into the adjustment. A full variance-covariance matrix whose elements correspond to the accuracy of the georeferencing parameters and image points can be included in the adjustment. Obviously, at least two images are required for estimating $\mathbf{r}_{P}^{M}$.

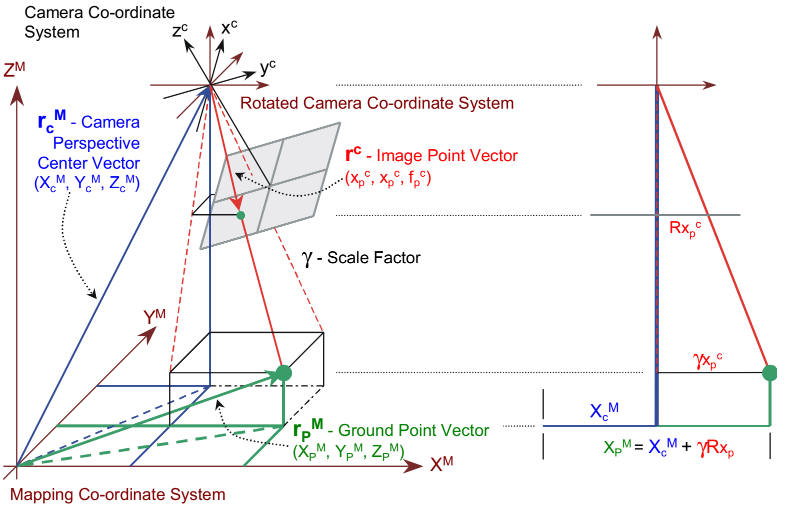

Figure 2: 3-D Co-ordinate Calculation using Georeferenced Images

For the backpack MMS to succeed in its goal of bringing mobile mapping into a wider market, user-friendly software is essential. Consequently, such software is being developed concurrently with the development of the backpack MMS. When completed, the software package will be capable of processing the navigation data, manipulating the images, and calculating the 3-D mapping co-ordinates of features visible in the images. The features of the software can effect the accuracy of the object points – for example the software uses Intel's® powerful and freely available Image Processing Library to perform geometric and radiometric enhancements to the images. This can aid the user in point selection. A screen-shot of the software in its current stage of development is shown in Figure 3. Visible are the epipolar lines that aid in point selection from multiple images. Once collected, the points and features can be easily exported to a GIS.

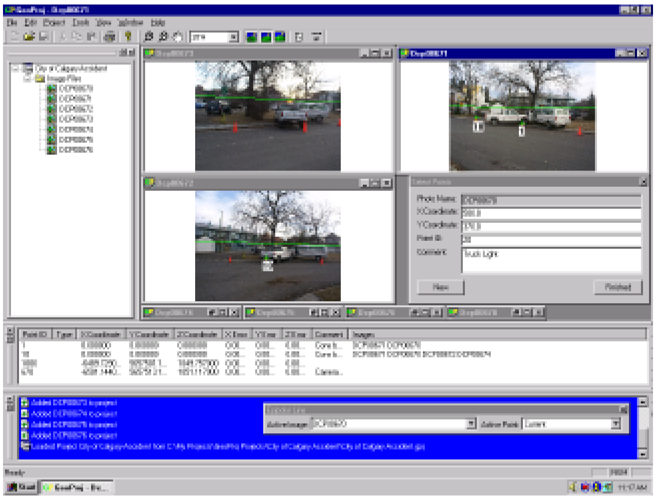

Figure 3: 3-D Feature Extraction Software

4 SYSTEM SIMULATION

From the analysis of Georeferencing sensors presented above, a number of possible sensor combinations appear suitable for a backpack mobile mapping system. These combinations are listed below in Table 3.

	System	Cost (USD)	Power Consumption	Comments
A	Single GPS antenna and tactical grade IMU	~$17 000	~16 W	IMU can bridge the GPS during signal blockage, redundant position information, heavy, high power consumption
B	High-accuracy 2-axis tilt sensor and dual-antenna GPS	~$9500	~8.5 W	Redundant attitude information
C	Low-Accuracy 2-axis tilt sensor with a dual-antenna GPS	~$7000	~8.5 W	Redundant attitude information
D	3-Axis Magnetometer/2-Axis tilt Sensor and single antenna GPS	~$6000	~6.5 W	Magnetic sensor is sensitive to external magnetic fields, smallest size

Table 3: Possible Sensor Combinations

A number of assumptions are made in Table 3. Firstly, the prices listed above do not include the cost of the digital camera, logging computer, power supply, or other incidentals that are also required by the system. These costs are essentially the same for all systems, and are approximately $2000 – $2500 US. Secondly, the power consumption figures do not include the digital camera's or logging computer's power requirements. Both, however, typically have their own power supply. Thirdly, the GPS receivers are assumed to be single frequency (L1) systems and the dual-antenna GPS system is assumed to use a single receiver to process the measurements from both antennas (commercial systems, such as Novatel's BeeLine®, use this technique). Finally, to receive real-time differential corrections an additional GPS receiver is required to serve as the base station. The cost of this additional receiver is not included in the above table as the majority of survey and mapping firms currently have existing GPS receivers that could be used as the base station, and therefore the purchase of an additional receiver would not normally be required.

To test the theoretical accuracy of the systems proposed in Table 3, a number of simulations were run using the systems described in Table 3 with the accuracies given in Tables 1 and 2. For these simulations it was assumed that the mapping sensor was a Kodak DC260 – a low-cost consumer digital camera with a maximum resolution of 1536 x 1024 pixels. Because the backpack MMS is designed for close range applications, it was also assumed that the lowest zoom setting would be used. This corresponds to a focal length of approximately 1700 pixels, and a field of view of approximately 48°. Neglected in the calculations are the effects of errors in the calibration of the system. However, these errors are not significant when compared with the accuracy of the navigation sensors. The relative offsets between the different sensor systems can be calibrated to mm level, and the differential rotations between the attitude sensors and the camera can be determined to several arc-minutes. Both accuracies are below the noise levels of the navigation sensors. The errors in the interior orientation parameters in the camera are included in the accuracy estimates for the selection of the image points. The imaging geometry for the simulations is shown in Figure 4. For simplicity, the images were considered to be facing the object point, and the image points were considered to be in the centre of the images. Considering the mobility of the backpack MMS, this configuration is reasonable.

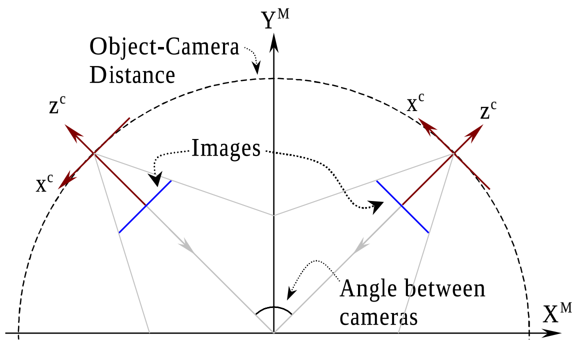

Figure 4: Imaging Geometry for Simulations

System Configuration	Attitude Angle Accuracy (Roll, Pitch, Azimuth)	Object – Camera Distance	Accuracy – Horizontal, *Vertical* (m) Angle Between Cameras 30°		60°		90°	
A, C, D	0.25°, 0.25°, 2.0°	10 m	0.39	*0.18*	0.23	*0.18*	0.20	*0.18*
	0.25°, 0.25°, 0.75°	20 m	0.45	*0.19*	0.26	*0.19*	0.23	*0.18*
	0.25°, 0.25°, 1.0°	30 m	0.54	*0.20*	0.31	*0.20*	0.27	*0.19*
B	0.05°, 0.05°, 0.75°	10 m	0.37	*0.18*	0.21	*0.18*	0.19	*0.18*
		20 m	0.38	*0.18*	0.22	*0.18*	0.19	*0.18*
		30 m	0.40	*0.18*	0.23	*0.18*	0.20	*0.18*

Table 4: Simulated Object Point Standard Deviation – 2 Cameras, L1 RTK GPS

When the simulations were run using L1 RTK GPS as the positioning sensor, configurations A, C, and D gave, to the nearest centimetre, the same results. Not surprisingly, the small differences in the accuracy of azimuth determination between these sensor configurations do not significantly effect the accuracy of the object co-ordinates – certainly not at the object to camera distances at which the backpack MMS will be expected to operate. Because of the closeness of results between the different attitude sensor systems it is clear that the driving factor behind the accuracy of the object points is the accuracy of the GPS. The effect of different types of GPS positioning on the object points is shown below in Figure 5.

GPS Type and Accuracy (Horizontal, *Vertical*)	Object – Camera Distance	Accuracy – Horizontal, *Vertical* (m) Angle Between Images 30°		60°		90°	
L1 Precise Ephemeris 1.0 m, *3.0 m*	10 m	2.01	*2.12*	1.16	*2.12*	1.01	*2.12*
	20 m	2.03	*2.12*	1.17	*2.12*	1.01	*2.12*
	30 m	2.05	*2.12*	1.18	*2.12*	1.02	*2.12*
Code Differential 0.75 m, *1.0 m*	10 m	1.50	*0.71*	0.87	*0.71*	0.75	*0.71*
	20 m	1.52	*0.71*	0.88	*0.71*	0.76	*0.71*
	30 m	1.55	*0.71*	0.90	*0.71*	0.78	*0.71*
L1 Post-mission 0.02 m, *0.03 m*	10 m	0.14	*0.04*	0.08	*0.04*	0.07	*0.03*
	20 m	0.27	*0.07*	0.16	*0.06*	0.13	*0.05*
	30 m	0.40	*0.10*	0.23	*0.09*	0.20	*0.08*

Table 5: Simulated Object Point Standard Deviation – 2 Images, Sensor Configuration D

The tables above demonstrate the effect of imaging geometry on the accuracy of the 3D co-ordinates of the object points. Figure 5 is a graphical representation of the relationship between geometry and accuracy. As noted previously, one of the benefits of a backpack MMS is that a user will virtually always be able to take advantage of the best possible geometry. An additional advantage of a backpack MMS is that a user is free to capture as many images as desired of a feature – something that is not typically possible with airborne or vehicle mounted mobile mapping systems. However, as shown below in Table 6, an increased number of images does not significantly improve accuracy – certainly the improvement is not as significant as the improvement from using the best possible geometry. Note that this simulation assumed that all images were captured on one side of the feature. Having the camera positions equally spaced around the entire object would give better results but such a camera configuration will not, in general, be possible.

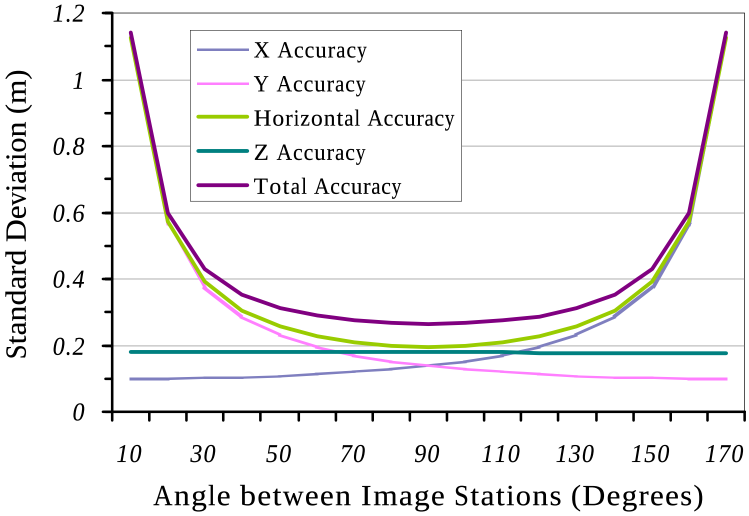

Figure 5: Simulated Ground Point Standard Deviation – 2 Images, Sensor Configuration D, 10 m from feature

Number of Images	Object – Camera Distance	Accuracy – Horizontal, *Vertical* (m) Angle Between Images 30°		60°		90°	
3 Images	10 m 20 m 30 m	0.21 0.25 0.30	*0.15* *0.15* *0.16*	0.16 0.19 0.22	*0.15* *0.15* *0.16*	0.17 0.20 0.24	*0.15* *0.15* *0.15*
		20°		40°		60°	
4 Images	10 m 20 m 30 m	0.20 0.23 0.28	*0.13* *0.13* *0.14*	0.14 0.16 0.19	*0.13* *0.13* *0.14*	0.14 0.17 0.20	*0.13* *0.13* *0.13*

Table 6: Simulated Object Point Standard Deviation – L1 RTK, Sensor Configuration D

The final simulation repeats the test conducted in the first simulation, but considers that the cameras are not facing the object point, and that the image point is on the edge of the image. Figure 5 shows the imaging geometry in this case. Because of the narrow field of view of the camera, the convergence angle between the images is relatively small. In this case, the small differences in azimuth accuracy between the configurations do effect the results. However, horizontal accuracy for most distances and configurations remains well under 0.5 m. The results for this simulation are listed in Table 7.

System Configuration	Object – Camera Distance	Accuracy – Horizontal, *Vertical* (m) Angle Between Cameras 30°		45°	
A	10 m 20 m 30 m	0.39 0.45 0.54	*0.19* *0.23* *0.28*	0.28 0.32 0.38	*0.20* *0.27* *0.35*
B	10 m 20 m 30 m	0.37 0.38 0.41	*0.18* *0.19* *0.20*	0.26 0.27 0.29	*0.18* *0.19* *0.21*
C	10 m 20 m 30 m	0.39 0.45 0.54	*0.18* *0.19* *0.21*	0.28 0.32 0.38	*0.18* *0.20* *0.23*
D	20 m 30 m 30 m	0.39 0.45 0.54	*0.18* *0.20* *0.22*	0.28 0.32 0.38	*0.19* *0.21* *0.24*

Table 7: Simulated Object Point Standard Deviation – 2 Cameras, L1 RTK GPS

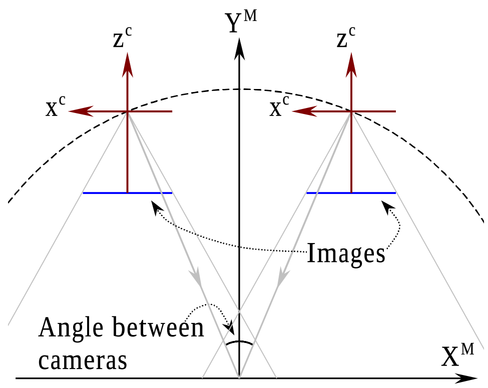

Figure 6: Imaging Geometry for Simulation in Table 7

5 CONCLUSIONS

Using low-cost off-the-shelf navigation and imaging technologies, the simulations performed above demonstrate that half-metre accuracies in the determination of object space co-ordinates are possible using a backpack mobile mapping system. With more precise GPS and multiple images, even higher accuracies can be obtained. These accuracies are comparable to the accuracies of current GIS data collection techniques, however the backpack MMS would offer increased efficiency and lower costs. Future research will focus on examining the real-world performance of the georeferencing sensors studied in the simulations.

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